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RESEARCH REPORT

Learners' knowledge in optics: interpretation, structure and analysis

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This study explored high school and teacher-training college students' knowledge of light, vision and related topics before and after commonly practised instruction. This knowledge was analysed and interpreted in the light of premises for the construction of alternative knowledge by learners of optics. A hierarchical structure was suggested to represent the collective conceptual knowledge of students in terms of facets and schemes of knowledge. `Abundance' and `gain' coefficients permitted quantitative description of the spread and alteration of the facets and schemes. In place of confronting misconceptions individually, schemes provide a basis for the design of more effective methods of instruction to challenge the fundamental *patterns* of alternative knowledge. Student misconceptions identified in other studies were included for comparison. On the basis of the study, suggestions are made for modifications in curricula to improve optics instruction.

Introduction

An interest in the content and structure of students' knowledge is fundamental to the constructivist understanding of learning sciences and to the designing of science curricula and teaching tools (e.g. Tobin *et al*. 1994). This aspect is shared also by opponents of radical constructivism (Solomon 1994, Osborne 1996) who do not deny the effectiveness of constructivism and the relevance of its teaching implications. The complexity of the cognitive processes involved in learning makes the study of the cognitive system itself, in `micro', complicated and causes it to involve many assumptions (Niedderer and Schecker 1992). Therefore, the `macro' approach, the description of the products of learning, would present a valuable complementary component and facilitate practical implications. Most scholars interpret learning as the construction (instead of acquiring) and assimilation (instead of adoption) of knowledge using the cognitive tools available to an individual (e.g. Gilbert *et al*. 1982, Glaserfeld 1992, Smith *et al*. 1993, Driver *et al*. 1994). This perspective encourages efforts to elicit data regarding the content and organization of students' knowledge before and after formal instruction. An understanding of the conceptions held by students, the ways in which their conceptions are employed and of how they deviate from contemporary scientific thinking has become of great value. Such knowledge is fundamental for our understanding of learning; it informs us about the particular difficulties that the learner faces and is essential for the design of improved, more effective instructional materials.

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(Wheatley 1991). Our study explored such knowledge in the particular scientific domain of optics.

Study background

Of all the senses, vision is the most valued. Normally, it delivers a large majority of all sense information to the individual. In their spontaneous efforts to make sense of the surrounding world, children construct explanations for many optical phenomena. As a result, an abundance of knowledge is spontaneously formed before any formal learning takes place. Many studies have explored children's knowledge about light, vision and optics phenomena (Stead and Osborne 1980, Jung 1987, Andersson and Karrqvist 1983, Goldberg and McDermott 1986, 1987, LaRosa *et al*. 1984, Watts 1985, Guesne 1985, Feher and Rice 1988, 1992, Ramadas and Driver 1989, Perales *et al*. 1989, Saxena 1991, Bendall *et al*. 1993, Osborne *et al*. 1993, Shapiro 1994, Selley 1996a, Langley *et al*. 1997). In these studies the alternative knowledge possessed by students with regard to optics phenomena was assessed and found to be different from formal scientific knowledge. In contrast to the view that intuitive knowledge is `...a loose group of tribes rules by ad hoc and inconsistent rules', some (e.g. Jung 1987, Bouwens 1987, Rice and Feher 1987, Fetherstonhaugh and Treagust 1992, Reiner 1992, Galili *et al*. 1993, Ronen and Eylon 1993, Selley 1996) have looked for an organization in such knowledge. Guesne (1985) and Selley (1996a) reported a model of `active' vision, Rice and Feher (1987) talked about the holistic paradigm regarding images and shadows, and Galili, Bendall and Goldberg (1993) discussed the students' image projection model. In the clash between the spontaneous and formal interpretations of nature new conceptions develop - heuristic (Feher and Rice 1988), hybrid (Galili *et al*. 1993) or synthetic (Vosniadou 1994). The present study explored this subject further.

Peculiarity of knowledge in optics

Students find the subject of optics to be obscure and difficult and teachers' help often insufficient. Scientists have also considered light and vision to be troublesome subjects through a 2500 years long history. It is instructive therefore to formulate factors which serve as premises (P) for obstacles in the construction of scientific (as well as individual) knowledge about optical phenomena. Some of these factors are intrinsic and impede the reduction of optical theory to simple and valid explanatory models. Others may be removed by an appropriate effort.

P-1. The physical parameters associated with light, e.g. its speed, wavelength, pressure and discrete nature, are all far removed from the range of perception of the human senses, the range of an individual's experience. In everyday life there is no time lag due to the finite speed of light. The processes of image formation, the spreading of illumination and many other observed optical phenomenon seem to be instant. Our experience confirms neither the wave nor the particle nature of light. In contrast with the scientific claim, light appears as stationary and continuous. Macroscopic optical phenomena are perceived through an unconscious integration of microscopic signals and, as such, their analysis was reserved for the speculative theories developed over the generations.

P-2. Optical phenomena are commonly observed in media (air, water) which often greatly modify the behaviour of light from that in vacuum. This `intrusion' is ubiquitous and very difficult to account for. The modified optical phenomena (light scattering, creation of various halos, light glows) impede on interpretation in terms of elementary optics (e.g. Minnaert 1940). At the same time, the everyday exposure of children to these phenomena influences their construction of spontaneous knowledge about light so that it conforms with direct perception. Artists and writers reflect on the human perception of the sky as luminous (`the bright sky full of light'), or of a glow, as a light sphere around the light source. Thus, Van Gogh portrayed such a glow round a candle in *Le Sedia di Gauguin*, and halos in the starry sky in *Esterno di Caffe di Notte*. Similarly Ernst Mach (1926: 10) records his lasting impression as follows:

> Having spent my youth on a great plain, I often saw how, when the setting sun cast its rays through rifts in the clouds, these rays, forming great circles in the heavens, coalesce again on the horizon at the opposite point from the sun as a perspective image of a parallel bundle of rays on the spherical dome of the sky.

P-3. The observer in optics is an inherent part of the optical system. Normally in the classical physics, effort is invested to exclude the disturbance caused by the observer. Not so in optics, where an account of the observed phenomenon presumes an inclusion of the observer's eye as a part of the optical system. Nothing indicates to the observer his/her true physical role, since vision and light delivery to the eyes are not accompanied by perceptible muscular effort. The progress of seeing (i.e. interpretation of visual images), like breathing, operates subconsciously.

P-4. Language brings problems of a psychological nature. Historically, language was developed under the influence of visual perception and well before our present understanding of vision was reached. Thus many linguistic constructions do not conform to present-day scientific knowledge. Phrases such as `her eyes shine', `his face radiates light', `she casts a glance', `light fills the room', `the mirror reflects images' and `the tree casts its shadow' are at odds with contemporary optics. Physics instructors often express a wish to obliterate the `verbal nonsense' which students associate with terms such as light, sight, image, shadow, reflection and focus. They feel that, although naive interpretation of these terms serve well in every day life, it `must be shed in order to attain genuine understanding' (Arons 1995).

P-5. Humans spontaneously explain phenomena in terms of cause and effect. In this exercise, they are guided by `common sense' which, admittedly, often suffices for achieving everyday goals. Scientists were not immune from this trend. Thus early scientific theories often leaned heavily on everyday experience, straightforward interpretations and superficial reasoning. Cognitive situations of contemporary learners are often similar and, indeed, we find students' views, beliefs and ideas clearly reminding us of early theories. For example, the concepts of the moving image (eidola), vision rays, static light and its instantaneous expansion (Ronchi 1970 Lindberg 1976, Park 1997) were all detected as being held by students. It is now realized that primitive (`common sense') reasoning may greatly mislead the novice learner seeking for adequate knowledge in optics.

P-6. Optics is essentially an interdisciplinary subject. Physics (the nature of light), physiology (the functioning of the eye) and psychology (the interpretation of visual and colour perception) are all needed for comprehensive discussions of optical phenomena (Feynman *et al.* 1964, Gregory 1979). Optics instruction using only physics is limited and cannot confront spontaneous knowledge about light. Such instruction often cannot explain those natural phenomena which intrigue the novice learner.

P-7. Optics instruction is heavily based on graphic symbolism, which is subject to interpretation. A number of commonly adopted conventions of graphical coding are often tacitly presumed. Their interpretation by the learner is usually idiosyncratic and conforms to previous knowledge. For example, randomly exchanged top and front views, minimal ray diagrams lacking `irrelevant' details, arrows in multiple meanings, etc. are common in textbooks (Beaty 1987). Some auxiliary graphical tools, such as light rays (prevailing in computer software), may acquire a different meaning in students' interpretation from their scientific version (Galili *et al*. 1993, Galili 1996).

Framework of approach

Intuitive knowledge reflects students' daily experience and guides their activity. An amazing feature of human cognition is that it does not stop at establishing *rules* which would be sufficient to guide for practical goals, but proceeds, seeking for *explanations* (Gilbert *et al*. 1982, Driver *et al*. 1985).This implies a reduction of knowledge to cause-effect constructs, logical interpretations of reality which, for some reason, provide the individual with a feeling of comfort. However, being heavily based on appearance, students knowledge (as anticipated above) cannot be but speculative and have little chance to be scientifically correct. It is subjective and context dependent, lacking in commitment to cross-domain consistency which is standard in scientific approaches. However, this does not exclude such knowledge from being organized and, in a way, coherent.

`Common sense theory' (e.g. Mariani and Ogborn 1991) and `Knowledge in pieces' (diSessa 1993) reflect such organization, ranging from extended causal structures to the view of nuclei of organized cognition, `phenomenological primitives' (p-prims). The question of hierarchy in such structures deserves inquiry. If its exists, such a hierarchy should incorporate a variety of constructs constituting student knowledge. Minstrell (1992) suggested describing such knowledge of a situated nature in terms of `facets and knowledge' which represent cognitive unit of reasoning or strategy applied by students when addressing particular situations. Facets reflect the conceptual, operational and representative ideas and beliefs of children (e.g. Minstrell 1992, Galili and Bar 1997). By tracing changes in facets of knowledge, it is possible to discover how knowledge increases and undergoes reorganization throughout the learning process. Once they have been elicited, facets may be used to guide the efforts of educators to achieve conceptual changes, for example using a sequence of anchoring analogies (Clement *et al*. 1987). Conceptual changes can be described in terms of facets, their alternations and shifts (e.g. Dykstra 1992).

One can further investigate the relationship of facets of knowledge to p-prims on the one hand and schemes of knowledge (Galili 1995, Galili and Kaplan 1996, Galili and Lavrik 1998), on the other. Schemes of knowledge, are other elements in knowledge architecture, conceived by us as representing a more inclusive unit of higher level of abstraction. As such, each scheme is affiliated to a cluster of facets which represent its realization in various situations. A scheme exposes the common core explanatory pattern deployed by an individual for addressing different settings. This approach was used by Galili and Lavrik (1998) to describe students;

knowledge about seasons and illumination. The facets-scheme approach is also exemplified by the results of the present study. Thus, in investigating students' prepositions about the optical image, we elicited the following facets addressing settings with a plane mirror:

Facet 1: The image stays in the mirror whether or not it is observed. (Although you do not see it, others can.)
Facet 2: The image moves from the object towards the mirror, where it stays (The observer is not involved.)

At the same time with regard to image formation by a convex lens they predicted:

Facet 3: When the screen moves towards or away from the lens the image will become bigger or smaller but remain sharp.
Facet 4: A half-lens produces a half-image. The rest of the image (rays) is blocked.

In light of all the four facets one can arrive at a general pattern of understanding an image as *a corporeal replication of an object which might move, remain stationary, or turn as a whole*. The latter was interpreted by us as a scheme of knowledge representing a common idea underlying the facets. It is clear that eliciting of schemes and their correspondent clusters of facets is a challenge.

Obviously, student schemes of knowledge may not conform to scientific conceptions and may represent alternative interpretations of subject (see the many examples below). Free form the constraint of mutual consistency, different schemes can coexist and complement each other in a variety of structures. Although we do not know to what extent schemes truly express learner's cognitive arrangements, we can use them as if they do, to adequately represent students' knowledge, to account for the learning process and to plan effective teaching. The goal of our study was to discover the relevant knowledge of students and to represent it in a facets-scheme hierarchical structure, sensitive to the type of instruction. Some results of other studies were subjected to the same interpretation.

Sample

Our data were accumulated by testing representative samples of high school (tenth grade) and college (teacher-training college) students for their conceptual knowledge of optics. To increase the generalizability of the results, the sample included several types of Israeli high schools. The student population learning physics, a required course in the tenth grade, is commonly heterogeneous, whereas in higher grades only a small proportion choose to study physics within an elective (advanced placement) course.

Our sample consisted of 166 student divided into two groups, representing sub-samples both before and after being instructed in geometrical optics. Three ninth grade classes (public urban, boarding and regional comprehensive high schools) made up the pre-instructed group (64 students). The post-instructed group (102 students) was comprised of students form three tenth grade classes in the same schools, plus a class from a teacher-training college (prospective teachers of technology). The currently adopted curriculum prescribes 40 hours of instruction in geometrical optics. A comparison of our results with those of previously published reports showed a similarity in the raw data. To illustrate this similarity (which supported the generalizability of our findings and of the inferences made) we included some relevant output from other studies with our own results, and will interpret them in a common manner.

The comparison between the two groups is justified by the fact that both were made up of populations drafted from the same schools so that the classes were equivalent in all besides the experience of instruction.

Instruments of assessment

The format of a written questionnaire was chosen as most appropriate for investigating a sample of 166 students. We utilized questions which had been used in previous studies of the subject (where their validity and effectiveness had been proved in interviews) together with new ones of our own design. The questions addressed the content knowledge and the conceptions held by students about light, vision, light behaviour and related topics. To increase the reliability of the collected data the questions used were qualitative and had an open format. We thus obtained data of greater diversity and higher reliability than we would have collected in a rigid structure multiple-choice test. Inquiry into each conceptual area was made by more than one question, thus enhancing both the validity and the reliability of the results. Checking the same issue in different settings also facilitated the elicitation of the facets-scheme structure of knowledge. The content validity of the questionnaire and its relevance to our goals was due to the competency and professional expertise of the researchers, qualified and experienced members of faculty in physics and physics education. It was further confirmed in discussions with colleagues of similar qualifications.

Our questionnaire comprised 13 questions addressing conceptual understanding of:

- the act of vision (the role of light and that of the eye, light as an object);
- general properties of light (light in space, light emanating from a source, light passing through a pinhole);
- shadow formation;
- imagery in reflection and refraction (image formation and location in relation to the observer and the screen);
- colour resulting from coloured radiation and from reflection.

Testing was carried out in a regular class environment, in a period of 45 minutes and students were encouraged to draw diagrams or sketches to support their written answers.

Analysis of the results was aimed at characteristics of knowledge and articulation of student understanding of optics. Qualitatively this was attained through a facets-scheme hierarchical organization. Coefficients were introduced to facilitate quantitative evaluation. The abundance of each facet of knowledge was represented by FA (FA_1 prior to the instruction and FA_2, after it). To represent the influence of instruction on a facet, we used a coefficient of `facet gain' (FG). Similarly, the `abundance' of a scheme was characterized by a coefficient SA (SA_1 and SA_2). Finally, the `gain' coefficient SG measured the influence of the instruction on the scheme abundance. All coefficients are defined and explained in the Appendix.

Preliminary qualitative and quantitative interpretation of data

This study did not focus on the evolution of views reflecting the cognitive maturation of individuals (Selley 1996b), but rather on the conceptual knowledge of learners before and after instruction. We have not reproduced the raw data, partly because of its extent and also because there is no shortage of this in the literature. Where appropriate, we present, within the same facets-scheme structure, qualitative findings of other researchers who have explored the subject (table 9). This enabled us to generalize about students' knowledge and analyse it qualitatively regardless of the method of instruction.

Vision, the role of light and eye

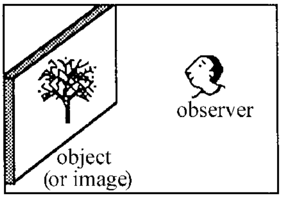
Table 1 shows those facets of knowledge which can be interpreted as manifestations of the Scheme of Spontaneous Vision. The scheme implies that vision is an activity performed naturally by the eye (with no physical contact with outside reality). Corresponding to premise P-3 above, the scheme leaves vision without any explanatory model providing a material link between the observer and the objects observed. This understanding of vision represents the initial stage in a succession of models of rising complexity that an individual adopts in the course of knowledge development (Guesne 1985, Bendal *et al.* 1993, Selley 1996b). The scheme was found to be pronounced both prior to instruction (SA_1 =64%) and afterwards (SA_2 =46%). In many cases, in replying to a question about how we see things, students did not show any link between the eye and the observed object or image (Facet 1-1, Galili *et al.* 1993, Bendall *et al.* 1993), sometimes they used expressions such as `eyes can see', or `I just open my eyes, and I see' (Facet 1-2). Students mentioned the necessity of turning towards the observed object, `to aim eyes at it', `to focus on it' (Facet 3), a behaviour different from that associated with hearing. Another `sufficient' condition for an object being seen was said to be its location in the `field of vision (Facet 1-4). Some regarded light itself as a subject of vision, a bright object which eyes observe `from the side'. Some believed that light travels through space, while others regarded it as a stationary entity (Facet 1-5). Facet 1-6 (light as a necessary background for vision), Facet 1-7 (light as an illuminating agent), and Facet 1-8 (light as triggering vision) represent previously reported views.

Nature and properties of light

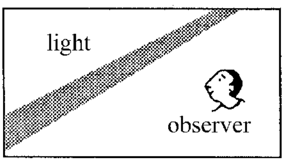
Students' ideas about the nature of light include the Corporeal Light Scheme. Within this scheme, students think of light as an object in space, or sometimes on a surface (a screen, illuminated surface), a subject of observation (Facets 2-1 and 2-2). In this scheme vision and light are interdependent, and are often defined in a circular manner—light as a cause of vision and vision as due to light. Naturally, the schemes of knowledge with regard to vision and the nature of light are closely related in the learner's perception. The contiguity between schemes 1 and 2 is manifested by the fact that they share the same facet. `Light staying or travelling in space can be seen from the side' may testify equally to the Spontaneous Seeing Scheme (Facet 1-5) and the Corporeal Light Scheme (Facet 2-2). This reflects the fact that the same proposition can express more than one idea. The scheme reveals a static understanding of light as an entity that fills space and remains in it (Facet

Table 1. The facet contingency of the Spontaneous Vision Scheme (seeing happens naturally as a result of the presence of the eye).

#	*Facets of Knowledge*	FA_1 (%)	FA_2 (%)	FG (%)	*Source*
1-1	In sketches and ray diagrams supported by explanations, no reference is made to a connection/relation between the eye and the observed object/image on screen, mirror, etc.	+([1])	+	−([2])	GBG ([3])
		+	−	−	BGG



#	*Facets of Knowledge*	FA_1 (%)	FA_2 (%)	FG (%)	*Source*
1-2	In students' written descriptions and sketches describing the vision process, no reference is made to a *physical* relation between the observing eye and the observed objects.	60	44	16	ps
1-3	To see an object one aims or `focuses' the eyes on it, applies attention to it, looks at it.	81	41	40	ps
1-4	Objects are observed only if they are located in the observer's field of vision and are not blocked.	0	47	−47	ps
		+	−	−	LRE
1-5	Light can be seen from the side (provided that nothing blocks vision).	50	51	−1	ps



#	*Facets of Knowledge*	FA_1 (%)	FA_2 (%)	FG (%)	*Source*
		+	−	−	AK
1-6	Light is a supportive background which improves vision.	+	−	−	W
		+	−	−	AS
		+	−	−	LM
		+	+	−	B
		+	+	−	J
		+	+	−	SO

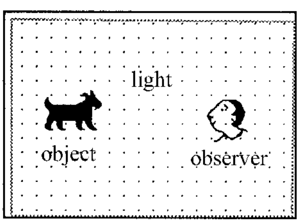
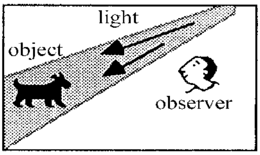
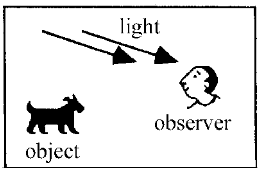


Table 1. (Continued)

#	*Facets of Knowledge*	*FA*$_1$ (%)	*FA*$_2$ (%)	*FG* (%)	*Source*
1-7	Light is needed to illuminate the object so that it can be seen by the eye.	+	–	–	BGG
		+	–	–	S
					
1-8	Light is needed to illuminate eyes, thus enabling their functioning.	+	–	–	BGG
		+	–	–	S
					

Scheme Abundance before instruction: $SA_1 = 64\%$	Scheme Abundance after instruction: $SA_2 = 46\%$	The gain of the scheme in the present study: $SG = -18\%$

([1]) `+' indicates that the facet was registered in the particular population.
([2]) `–' stands for not reported, not available, not relevant.
([3]) A key to abbreviations of authors' names is presented in table 9, `ps' represents `present study'.

2-3) or resides in a glow around a source (Facet 2-4). A consideration of the role of light rays provides further information. Rays were conceived literally as material constituents light (Facets 2-5, 2-6). Illumination is reached due to the `spreading of light rays' (Facet 2-7). During reflection and refraction light rays `bend', `break' and `bounce away' (Facet 2-8). As instruction on elementary optics lacks any model which would explain the peculiar behaviour of rays, it is likely that students perceive rays in a concrete manner.

Another scheme which emerged from data concerned with emanating light can be represented by the claim that a `Single ray is emitted from each point of the light source' (table 3). It has been termed the Flashlight Scheme. Although not incorrect, this scheme represents incomplete understanding from a scientific point of view. It incorporates the idea of rectilinear expansion of light (Facet 3-1), but it lacks the more representative picture of multiple rays emanating from *each* point of the source in *all* directions. The latter is essential in understanding many optical phenomena. The perception of a glow around a light source is often represented by radial rays (figure 2-a) instead of the more precise version in which rays are emitted from all parts of the source in all directions (figure 2-b). In sketches by children (figure 1), as well as by adults (e.g. Van Gogh's *Sower*), emanating light is

Table 2. The facet contingency of the Corporeal Light Scheme (light is reified).

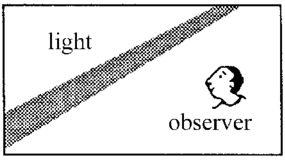
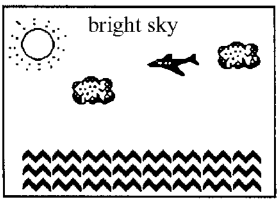
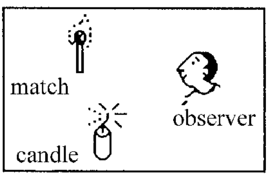
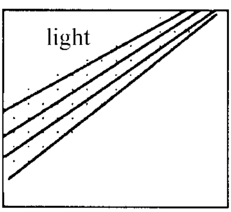
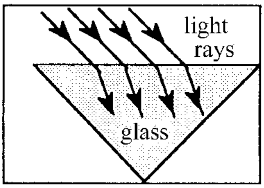
#	*Facets of Knowledge*	FA_1 (%)	FA_2 (%)	FG (%)	*Source*
2-1	Light is bright (shines) and therefore it is better seen in darkness.	51	50	1	ps
2-2	Light can be seen from the side (provided that nothing blocks vision).  	50	51	−1	ps
2-3	Light fills space and remains stationary (hence, the sky is bright).  	+	–	–	BGG
2-4	Light remains as a glow around a light source (candle, match, bulb, fire).  	75	41	34	ps
		+	–	–	BGG
		+	–	–	G
2-5	Light is comprised of (many or an infinite number of) light rays which fill space.  	68	58	10	ps
		–	+	–	BGG
		+	–	–	LM
		–	+	–	RE
2-6	Light rays resemble fibres in a rope.	+	–	–	W
2-7	Light rays spread and illuminate space or surfaces (rooms, walls).	+	–	–	LM

Table 2. (Continued).

#	*Facets of Knowledge*	FA_1 (%)	FA_2 (%)	FG (%)	*Source*
2-8	On entering a lens or prism light rays break (bend) and deviate from their straight course 	0	36	−36	ps

Scheme Abundance before instruction: $SA_1 = 61\%$	Scheme Abundance after instruction: $SA_2 = 45\%$	The gain of the scheme in the present study: $SG = -16\%$

represented by radially diverging straight lines. Clearly this representation (Facet 3-2), cannot fully support the scientific algorithm of image construction. When asked to predict the illumination pattern on a screen opposite to a pinhole in a mask, with a bulb touching the pinhole, many students suggested that a small spot of light would appear opposite the pinhole and sketched a narrow beam of light radial to the bulb (Facet 3-3). Others suggested a moderate radial divergence of the light beam, especially if the opening was bigger than a pinhole (Facet 3-4).

When the question addressed a situation where the light bulb was at a distance from the pinhole, many students continued to predict a circular area of light (Facet 3-5) instead of a pinhole image on the screen; prediction of a pinhole image was exceptionally rare. Students are commonly surprised when this is demonstrated (Bendall *et al*. 1993).

When asked to predict the illumination pattern when a mask with an opening in the shape of a key-hole was *attached* to the bulb, about a third in the pre-instructed and a quarter in the post-instructed samples predicted the appearance of a bright area in the form of the keyhole (Facet 3-6).

When presented with a converging lens, many students drew diagrams which revealed similar ideas, that light leaves each point of the source but moves solely in the `relevant' direction, namely radial (Facet 3-7) or horizontal (Facet 3-8) as was found by others (Galili *et al*. 1993). Though not totally mistaken, this view, being incomplete cannot facilitate a correct explanation of image formation and encourages an erroneous conception of image creation (see below).

The Flashlight Scheme was marked by relatively high abundance with respect to students knowledge before instruction and this was little changed by instruction.

Table 3. The facet contingency of the Flashlight Scheme (individual rays are emitted from single points on the light source).

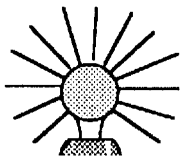
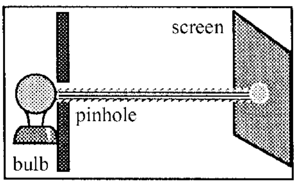
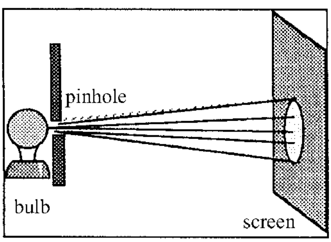
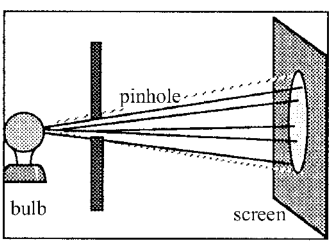
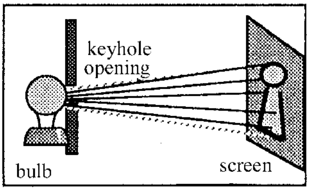
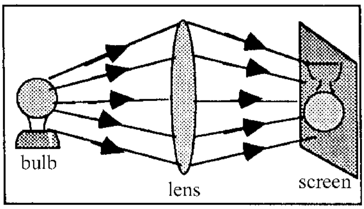
#	*Facets of Knowledge*	FA_1 (%)	FA_2 (%)	FG (%)	*Source*
3-1	Light expands (travels) in straight lines (represented by ordered and disordered lines on drawings).	46 +	61 –	15 –	ps BGG
3-2	When indicating light being emitted from an isolated source, students present straight lines, radially expanding from it. Each ray travels from one point on the source. 	37	44	−7	ps
3-3	Light passing through a small aperture is shown as a cylindrical beam. 	35	34	1	ps
3-4	Light passing through a small aperture is shown as a conical beam, gradually spreading out towards the screen. 	36	55	−19	ps
3-5	The size of a bright spot on a screen increases with the distance of the bulb from the aperture. 	0	18	−18	ps.

Table 3. (Continued).

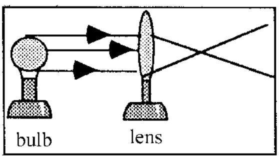
#	*Facets of Knowledge*	FA_1 (%)	FA_2 (%)	FG (%)	*Source*
3-6	The bright spot on a screen has the same configuration as that of an aperture placed between the screen and the source. `Only certain light travels to the screen.'	33	26	7	ps



#	*Facets of Knowledge*	FA_1 (%)	FA_2 (%)	FG (%)	*Source*
3-7	Students use the radially diverging light from a bulb to predict an image produced by a lens on a screen.	46	0	46	ps



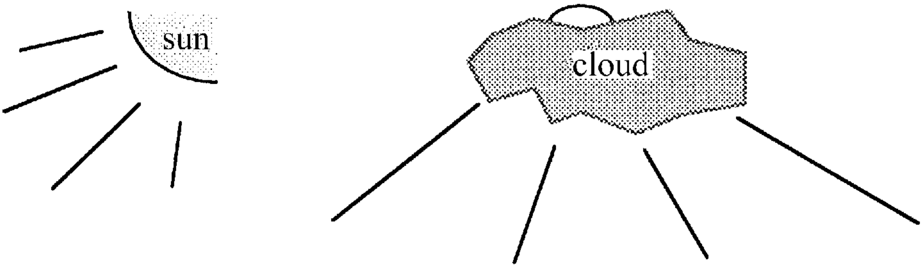
#	*Facets of Knowledge*	FA_1 (%)	FA_2 (%)	FG (%)	*Source*
3-8	Students ignore all the light diverging from a bulb except the part travelling directly to the target object (lens).	+	+	–	GBG



Scheme Abundance before instruction: SA_1 =39%	Scheme Abundance after instruction: SA_2 =40%	The gain of the scheme in the present study: SG =+1%

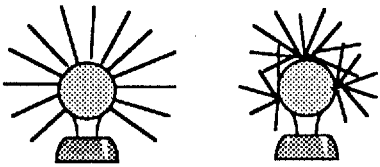
Imagery

Imagery is central in optics curricula. It is relevant for the topics of illumination (pinhole images), reflection (mirror images), refraction (lens and prism images) and shadows. Students' knowledge about images is versatile and often pronounced (Goldberg *et al*. 1991, Galili *et al*. 1993, Bendall *et al*. 1993). Is there any framework encompassing these views? It was shown that students, before instruction often regard optical images in a holistic manner (Rice and Feher 1987, Galili *et al.* 1993), and in our study, this framework of thinking is represented by the Image Holistic Scheme which regards an image as a corporeal replication of an object which might move, remain stationary, or turn as a whole. Commonly, the adher-



(a) **(b)**

Figure 1. Common representations of light radiating from the sun. **(a)** The sun in a bright sky; **(b)** The sun is covered by a cloud. Here the appearance is especially confusing: 'rays of light' are 'literally observed', expanding radially from behind the cloud.



(a) **(b)**

Figure 2. Common representations of a glowing bulb. **(a)** Light expands radially (as from the sun); **(b)** Light expands radially from each point of the bulb. This, more representative illustration (of the 'cactus kind') is preferable for didactic purposes.

ents to this scheme did not hold any mechanism for image formation and transfer. The affiliated facets (table 4), show modifications of the same conception in different contexts. Students' drawings added to the meaning ascribed to the scheme and compensated for the absence of explicit verbal data. The assessment shows this scheme to be initially relatively abundant ($SA_1 = 52\%$) and strongly persistent. Although its abundance was lower after instruction, it remained in more than one third of the students ($SA_2 = 35\%$), confirming its high popularity and persistency. Another scheme representing knowledge of images is the Image Projection Scheme: 'Each image point is related to the corresponding object point by a single light ray which transfers it'. The high scheme gain suggests that instruction contributes markedly to the construction of this scheme in the course of learning (Galili *et al*. 1993).

The Image Holistic and Image Projection Schemes are closely related and some of their manifestations might look the same. However, while in the Image Holistic Scheme the image is always seen as a complete entity, in the Image Projection Scheme the image undergoes deconstruction to a collection of points, each being transmitted by means of a single light ray. This distinction can be seen in differences between Facet 4-11 and Facet 5-4. The image considered by many as a whole before instruction (as in Facet 4-11), was seemingly replaced in the course of instruction by its 'refined' version (as in Facet 5-4) incorporating light rays and preserving the rest of the scheme.

Table 4. The facet contingency of the Image Holistic Scheme (an image is a corporeal replication of an object that might move, remain stationary, or turn as a whole).

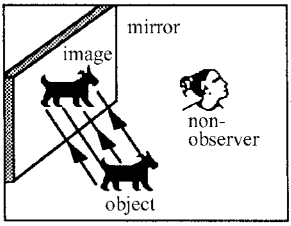
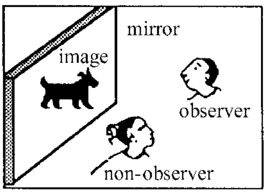
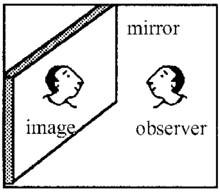
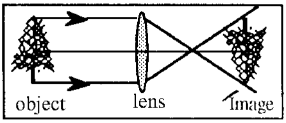
#	*Facets of Knowledge*	FA_1 (%)	FA_2 (%)	*FI* (%)	*Source*
4-1	An image moves from the object towards the mirror where it stays (observer is not involved).	+	–	–	BGG
					
4-2	The image is always present in the mirror whether or not it is observed. (Although you do not see it, others can.)	41	85	−44	ps
		+	+	–	GBG
		+	+	–	BGG
4-3	Images are first created by a special material comprising (or accommodated by) the mirror; subsequently we look at (in) the mirror and see them.	38	0	38	ps
		+	+	–	GBG
4-4	When we do not see the image in the mirror it is because it is not in our field of vision. (But it still exists and somebody else might see it.)	0	25	−25	ps
4-5	Mirrors duplicate (`reflect') objects by creating their images. Light may help (by stimulation or illumination).	50	0	50	ps
4-6	The image travels to the mirror and `bounces off it' (is reflected by it).	25	35	−10	ps
4-7	The image strikes the mirror and is reflected away from it at an equal angle.	0	27	−27	ps
4-8	Obstacles in its path prevent the image from reaching the mirror.	61	15	46	ps

Table 4. (Continued).

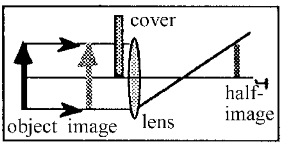
#	*Facets of Knowledge*	FA_1 (%)	FA_2 (%)	FI (%)	*Source*
4-9	A mirror inverses the image from right to left.	+	+	–	GGB-91
		+	–	–	GG-93
		+	–	–	BGG



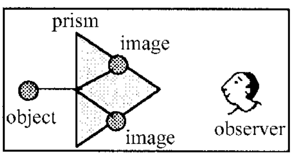
#	*Facets of Knowledge*	FA_1 (%)	FA_2 (%)	FI (%)	*Source*
4-10	A lens turns an image upside-down.	14	26	−12	ps
		+	+	–	GBG



#	*Facets of Knowledge*	FA_1 (%)	FA_2 (%)	FI (%)	*Source*
4-11	A half lens produces a half image. The rest of it is blocked.	87	30	57	ps



#	*Facets of Knowledge*	FA_1 (%)	FA_2 (%)	FI (%)	*Source*
4-12	If the screen moves towards or away from the lens the image becomes bigger or smaller but remains sharp.	78	50	28	ps
		–	+	–	GBG
4-13	When a converging lens is removed, a right-side-up image replaces the previously-observed inverted image.	53	19	34	ps
		–	+	–	GBG
4-14	We do not see light, we see images, (To see an image, it must enter the eye.)	+	+	–	(RD)
4-15	A triangular prism splits an image into two.	0	9	−9	ps



#	*Facets of Knowledge*	FA_1 (%)	FA_2 (%)	FI (%)	*Source*
4-16	Images are created (regardless of apparatus) and hence can be always obtained on a screen.	68	68	0	ps
		+	–	–	LM
4-17	Light does not create images, it only helps us see them.	+	–	–	W
		–	+	–	GM-87

Scheme Abundance before instruction: SA_1 =52%	Scheme Abundance after instruction: SA_2 =35%	The gain of the scheme in the present study: SG =−17%

Table 5. The facet contingency of the Image Projection Scheme (each image point is related to its correspondent object point by a single light ray which transfers it).

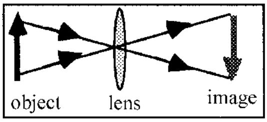
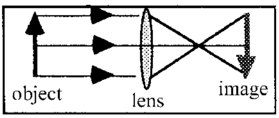
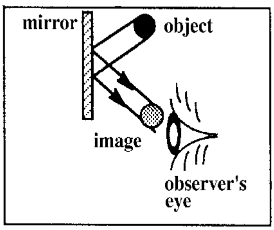
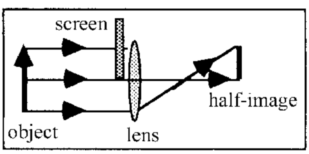
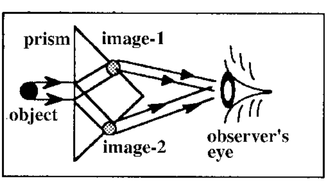
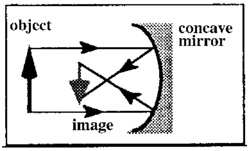
<table>
<tr><th>#</th><th>Facets of Knowledge</th><th>FA_1 (%)</th><th>FA_2 (%)</th><th>FG (%)</th><th>Source</th></tr>
<tr><td>5-1</td><td>A converging lens compels light rays to pass through its centre and an inverted image is obtained.
</td><td>5</td><td>45</td><td>−40</td><td>ps</td></tr>
<tr><td>5-2</td><td>Light rays bring an image to a lens. The lens bends the rays, making them cross at its focus and thus the image is inverted.
</td><td>0</td><td>37</td><td>−37</td><td>ps</td></tr>
<tr><td>5-3</td><td>Light rays bring an image to a mirror. The image is then reflected (bounced off) at the angle equal to the angle of incidence.
</td><td>0</td><td>46</td><td>−46</td><td>ps</td></tr>
<tr><td>5-4</td><td>When half of a lens is covered, half the light rays from the object are blocked, so only half of its image appears.
</td><td>0</td><td>60</td><td>−60</td><td>ps</td></tr>
<tr><td>5-5</td><td>A triangular prism creates two images by splitting light rays
</td><td>0
–</td><td>45
+</td><td>−45
–</td><td>ps
GBG</td></tr>
</table>

Table 5. (Continued).

#	*Facets of Knowledge*	FA_1 (%)	FA_2 (%)	FG (%)	*Source*
5-6	A concave mirror creates an inverted image by inverting the arrangement of the light rays. 	–	+	–	GBG

Scheme Abundance before instruction: $SA_1 = 5\%$	Scheme Abundance after instruction: $SA_2 = 47\%$	The gain of the scheme in the present study: $SG = +42\%$

The effect observed in the present study is impressive and indicative: a low initial abundance and a significant increase in the adoption of the knowledge related to the Image Projection Scheme (SG = +42%). It is difficult to refrain form a suspicion that this scheme is prompted by the instruction itself. Given that such an understanding of image formation is wrong, an unavoidable question arises regarding the suitability of instruction.

Shadow

Our results suggest that children can perceive shadows in much the same way as optical images. Table 6 includes ten facets recognized by us as manifestation of the Shadow Image Scheme and shows that there was little change, (SG = −3%) following instruction. All facets in table 6 reflect a holistic view. Thus, shadows can be manipulated as independent objects and can be added or subtracted (Facet 6-7). Facet 6-9 implies that shadows remain randomly oriented in space, regardless of any light source. The shadow of the object represents its shape (Facets 6-1, 6-5 and 6-10) much as its mirror image does and the light merely `make it visible' (Facet 6-4). These features show an affinity with other schemes. In fact, shadows are reified (as in Feher and Rice 1987) like images in mirrors and lenses. Interestingly, there is no room for partial shadows (penumbra) within the Shadow Image Scheme (Facet 6-8). In summary, one might unite all three schemes (Image Holistic, Image Projection and Shadow Image), in one framework of Image Conceptualization, to reflect the ways in which the image concept is cognitively elaborated (figure 3). This would introduce a three-level hierarchy: facets-schemes-conceptualization, to represent knowledge of optical imagery. It might also be appropriate in other areas and the idea suggests further study. A second scheme involving shadows, the Shadow Associative Scheme was also elicited. This relates shadows to the casual parameters of the environment (table 7), namely the power of the source (Facet 7-1), its size (Facets 7-2 and 3), its location relative to the object (Facet 7-4) and its position (Facet 7-5). Though none of these facets represents scientific ideas regarding shadow formation, none of them radically conflicts with any of them either. In fact, a change in any of the parameters

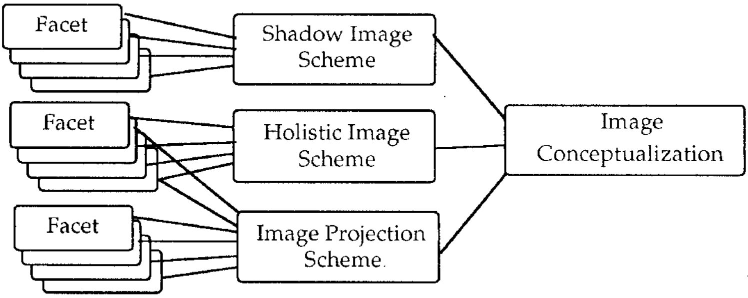


Figure 3. The hierarchical structure of students' knowledge regarding optical imagery.

Table 6. The facet contingency of the Shadow Image Scheme (a shadow is a kind of image separated from the object).

#	*Facets of Knowledge*	FA_1 (%)	FA_2 (%)	FG (%)	*Source*
6-1	A body gives its shape to the shadow it casts.	37	31	−6	ps
6-2	The shape of a shadow does not depend on the shape of the light source.	27	28	−1	ps
6-3	A shadow is a `reflection' (reproduction) of an object.	+ +	+ –	– –	FR-87/88 BGG
6-4	There is always a shadow and light `makes it seen'.	+	–	–	FR-88
6-5	A shadow is independent after it `leaves' an object.	+ +	– –	– –	FR-88 BGG
6-6	Light triggers the production of a shadow by a body/object.	+	+	–	FR-88
6-7	Shadows of objects can be manipulated (as a whole) by students (added and subtracted) to predict/explain shadow patterns.	+	–	–	BGG
6-8	Students do not predict partial shadows (penumbra).	+	–	–	BGG
6-9	In drawings, shadows are randomly oriented relative to the light sources.	+	–	–	LRE
6-10	Shadow appearance is not related to the blocking of light.	+	–	–	LRE
6-11	There is an absence of correlation in students' drawings between light distribution, the size and position of an object and its marked shadow.	+	–	–	LRE

Scheme Abundance before instruction: $SA_1 = 32\%$	Scheme Abundance after instruction: $SA_2 = 29\%$	The gain of the scheme in the present study: $SG = -3\%$

Table 7. The facet contingency of the Shadow Associative Scheme (shadow depends on environment).

#	*Facets of Knowledge*	FA_1 (%)	FA_2 (%)	FG (%)	*Source*
7-1	The stronger the source of light, the bigger the shadow.	18	22	−4	ps
7-2	A point source of light creates a vague shadow.	0	17	−17	ps
7-3	The bigger the source of light, the smaller the shadow.	0	8	−8	ps
7-4	The shadow of a body depends on the locations of light source and object.	20	0	−20	ps
7-5	An inclined light source casts an oblique shadow.	0	16	−16	ps
7-6	The greater the distance of the wall from the object, the bigger the shadow.	0	45	9	ps

Scheme Abundance before instruction: SA_1 =19%	Scheme Abundance after instruction: SA_2 =22%	The gain of the scheme in the present study: SG =3%

mentioned would, indeed, cause a change in the shadow pattern. Though comparatively modest in abundance, the Shadow Associative Scheme increased after instruction.

Colour

A pronounced Colour Pigment Scheme was elicited (table 8), according to which light and colour are independent physical entities. Thus, white light is regarded as the purest form of light, free from any tinge (Facet 8-7). The phenomenon of colour is ascribed to special materials (Facet 8-1) which, in the present context, are best described as pigments. These keep their individual identities in mixtures (Facets 8-2, 8-4, 8-6), where they compete with each other so that the strongest prevails (Facet 8-5). Facet 8-3 and perhaps Facet 8-8 seem to reflect personal experience of mixing pigment colours. The initial wide abundance of the colour pigment scheme prior to instruction, is not surprising (SA =50%), since its facets do not contradict everyday experience. However, its positive gain following learning (SG =5%) merits interpretation (see below).

Discussion

The knowledge shown by the subjects of this study, and the knowledge reported in studies of other populations, conform to the same organizing structure. We interpret this as support for the claim that the elicited schemes of knowledge are relevant to learners equally, regardless of differences in culture and education.

Table 8. The facet contingency of the Colour-Pigment Scheme (colour is different from light).

#	*Facets of Knowledge*	FA_1 (%)	FA_2 (%)	FG (%)	*Source*
8-1	Colour is due to a mixture of special substances different from light.	58	59	−1	ps
8-2	When mixed, lights of various colours remain separate.	27	0	27	ps
8-3	A mixture of coloured lights produces a somewhat darker light.	59	50	9	ps
8-4	Each colour in a mixture is perceived separately.	33	0	33	ps
8-5	In a mixture of colours, the most powerful prevails.	56	0	56	ps
8-6	Coloured lights mix like different liquids.	68	55	13	ps
		+	–	–	AS
8-7	White light is always bright and colourless.	+	–	–	FR-92
		+	+	–	B
8-8	Colours are produced by different stages of brightness.	+	–	–	LM
		+	–	–	FR-92

Scheme Abundance before instruction: SA_1 =50%	Scheme Abundance after instruction: SA_2 =55%	The gain of the scheme in the present study: SG =5%

Table 9. Abbreviations of the reports quoted in the study.

Key	*Source*	*Students' age*
AK	Anderson and Karrqvist 1981	13-15
AS	Anderson and Smith 1986	11
B	Bouwens 1987	14-18
BGG	Bendall, Goldberg and Galili 1993	college students
FR-87	Feher and Rice 1987	9-13 and college students
FR-88	Feher and Rice 1988	8-14
FR-92	Feher and Rice 1992	8-13
G	Guesne 1985	7-14
GBG	Galili, Bendall, Goldberg 1993	college students
GG-93	Galili and Goldberg 1993	college students
GGB-91	Galili, Goldberg and Bendall 1991	college students
GM-87	Goldberg and McDermott 1987	college students
J	Jung 1987	10-15
LM	LaRosa *et al*. 1984	13-14
LRE	Langley, Ronen and Eylon 1997	16 (before instruction)
RD	Ramadas and Driver 1989	13-14-15
RE	Ronen and Eylon 1993	15
S	Selley 1996a	9-11
SO	Stead and Osborn 1980	9-16
W	Watts, 1985	elementary school

Table 10. The appearance of Schemes of Knowledge.

#	*Scheme*	*Scheme content*	*Before abundance* SA_1(%)	*After abundance* SA_2(%)	*Gain* SG(%)
1	Spontaneous Vision Scheme	Seeing happens naturally as a result of the presence of the eye.	64	46	−18
2	Corporeal Light Scheme	Light is reified.	61	45	−16
3	Flashlight Scheme	Individual rays are emitted from single points on the light source.	39	40	+1
4	Image Holistic Scheme	An image is a corporeal replication of an object which can travel, remain stationary, or turn as a whole.	52	35	−17
5	Image Projection Scheme	Each image point is related to its correspondent object point by a single light ray which transfers it.	5	47	+42
6	Shadow Image-Scheme	A shadow is a kind of image separated from the object.	32	29	− 3
7	Shadow Associative Scheme	Shadow depends on environment.	19	22	+3
8	Colour-Pigment Scheme	Colour is different from light.	50	55	5

Schemes expose the underpinning conceptions and inform us about the patterns of reasoning employed by learners. Such knowledge facilitates practising teachers by helping them to analyse the range of student knowledge and to focus on its essence. Schemes of knowledge represent summaries of multiple facets. Therefore, changes in the abundance of schemes can be regarded as a reliable indicator of conceptual change. A negative gain for a particular facet (FG) may follow a direct instruction as a simple behavioristic effect and not be accompanied by a desired understanding. However, such local `progress' would not significantly influence the abundance of the scheme as a whole, which depends on contributions of a number of facets in the same cluster. Table 10 lists dominant schemes of knowledge regarding central topics of geometrical optics. Their prevailing character and high persistence in learners knowledge are reflected in high values of abundance coefficients (SA) and low values of gain coefficients (SG). We will use these schemes discussing traits of students' knowledge.

Vision (scheme 1)

Little progress was registered in refutation of the Spontaneous Vision Scheme subsequent to instruction. This might be because the usual instruction emphasizes the `objective' outside reality. Indeed, the subject of vision is hardly addressed in most introductory courses. The eye is mentioned in textbooks in the context of optical devices, as an example of a lens-based `gadget' along with other optical instruments. In the light of the warning of premise P-3 (see above), we realize why the explanations provided often miss correct scientific perception, the role of the observer (which is central in understanding many topics in optics) remains secondary or is even ignored.

This strategy is often justified by the complexity of the vision process and its relation to other disciplines. Following textbooks, physics teachers are reluctant to intrude into a domain which involves `extra' knowledge from psychology and biology. However, the elicited scheme of `natural', spontaneous vision, corresponding to premises P-1 and P-3 above, may justify the claim that the presentation of `optical' reality as existing independently and `not disturbed' by the observer, is inadequate in optics and may only reinforce alternative knowledge.

The academically justified sequence of presentation does not lend itself to the strategies of personal inquiry and individual construction of knowledge, which are heavilay based on visual sense data. Optics instruciton often takes for granted the essential fact that light must enter the eye for vision to take place. The need to convince the learner of this is seldom recognized.

Nature of light (schemes 2, 3)

The Corporeal Light Scheme implies that light itself is a subject for observation. The phrase `light in the air' corresponds to premise P-2. The scientific explanation involving scattering of light on dust or the air itself is far beyond common instruction in optics. Another effect seldom mentioned in optics instruction is `glow'. Scientifically this is ascribed to light scattering within the eye. Both topics are considered only in more advanced courses. Within the constructivist understanding of learning such a mismatch between instruction and actual observation is liable to give rise to alternative knowledge.

An important aspect of students' knowledge is confusion between light, as a physical entity and light as a sense perception. Young children normally do not distinguish between them (Guesne 1985) and, as our own results show, adult students very often suffer from the same confusion. In philosophy and psychology, this is attributed to there being a shortcut between the sense (of sight) and the constructed mental image (of light), in the relationship between `sensing and perceiving' (Mach 1926, Hirst 1965). Interestingly, the difference between sensing light and perceiving it was appreciated by the ancient Greeks and the medieval scientists in Europe and was reflected in the separate concepts of lux and lumen (Lindberg 1976). In modern science, two concepts apply to light; light flux (light as an entity) and light illumination (which determines perception of light). Although both these concepts were included in some high school and college optics courses (Sears and Zemansky 1955, 1977) in the not-too-distant past, they now seem to have disappeared from optics curricular and textbooks (Galili and Lavrik 1998). We cannot estimate the damage caused to students' knowledge of the nature of light by this change but the assumption that there has been some such effect seems plausible in the light of our findings.

Another topic related to the Corporeal Light Scheme which deserves special attention is the concept of the light ray. Almost any explanation in optics instruction involves rays. In modern understanding, the light ray is just a tool for representing the path of light. In students' knowledge, however, it is often regarded literally as a constituent of light, fitting Newton's perception of light as composed of light rays (Newton 1671, 1974: 76). Normally, textbooks in optics do not find it necessary to elaborate on this `semantic' distinction. The physical existence of rays is not denied and the term ray is undefined; it is presumed to be an obvious and self-explanatory construct. As a result, in students' minds the concept has an obscure meaning. Light rays are often assimilated as a `matter based', reified concept, instead of as a `process based' one. This confusion in ontological status may present a serious barrier in learning (Chi *et al*. 1994). Common schematic representations of light sources (figures 1, 2) also may lead to the same misconception. Above, with regard to premise P-2, we quoted Ernst Mach's description of the existence of light rays. Sunlight penetrating through leaves or clouds is commonly observed as `rays' and features in many pictures. In premise P-4 above we noted the possible influence of linguistic constructs to describe this reality. Do we address all these experiences in teaching optics? What is their influence on students' knowledge of light?

Imagery (schemes 4, 5)

Alternative understanding of optical imagery seemingly starts from confusion regarding the concept itself. The term is generally undefined in optics textbooks and learners are expected to assimilate its meaning by intuition. In fact, the term `image' is used in science in at least three different senses: these are real, virtual and pinhole images. Apart of the fact that all these are visual reconstructions of the object, they represent optically different things. To reduce confusion, some educators (e.g. Dykstra 1993, Goldberg *et al*. 1994) avoid referring to the illumination pattern on a screen behind a pinhole as an image, but the persistency and popularity of this term still seems very high. The development of students' understanding of optical imagery often follows the following path. The initially popular Image Holistic Scheme (expressing a strong commitment to the wholeness of an image) is gradually transformed, seemingly under the influence of instruction, to a kind of hybrid (Galili *et al*. 1993), or synthetic (Vosniadou 1994) knowledge. It often takes the form of Image Projection Scheme which is still essentially different form the scientific view. The gain of the latter scheme is very high (SG =42%). We attribute this to the heavy emphasis usually made in textbooks (and therefore also in instruction) on ray-diagram problem solving procedures, to a conceptual neutrality of formulae used in it and to the neglect of ideas related to light flux and illumination. Students' responses often reproduce memorized ray diagrams, reinterpreted and modified in keeping with alternative ideas regarding the nature of their constituents (warned about in premise P-7 above). Indeed, the Image Projection Scheme is based on an erroneous ontology of the light ray, which maps the object into its image, whereas the scientific model of image formation operates with object-image mapping by means of light flux, instead of single rays. This alternative understanding of image formation reflects the Alhazanian view of the tenth century (Lindberg 1976), an interesting fact that deserves interpretation (Galili 1996). Other implications of the deficiency of instruction were noted in connection with understanding seasons and illumination (Galili and Lavrik 1998).

Shadows (schemes 6, 7)

Students' understanding of a shadow as an image `cast by an object' which `light enables us to observe' presents ontological confusion similar to that mentioned above with regard to optical imagery. Reification of shadows in students' interpretation again shows their commitment to the idea of the reified image, the idea which appears with regard to each reproduction of objects by means of light. One way in which to discharge the erroneous cognitive shadow-image link is by teaching the shadow construction procedure in the setting of an extended light source which `disintegrates' shadow. It seems that students holding the views corresponding to the Shadow Image Scheme do not predict partial shadows (Bendall *et al*. 1993). This indicates that the scientific concept of partial shadow (penumbra) is barely compatible, if at all, with the holistic idea of shadow; the discovery by a student of penumbra thus may challenge the concept of shadow-image and encourage its reconsideration.

The Shadow Associative Scheme reflects the mechanism often used by individuals to make sense of reality, i.e. establishing a cause-effect link between the subject of interest (shadow) and a salient parameter controlling a particular setting (this corresponds to premise P-5 above). For example, it is true that distance between wall and object (other parameters being equal) determines the size of the shadow (Facet 7-6), but this knowledge is less effective than the formal procedure of shadow construction.

The high persistence of the Shadow Image and Shadow Associative Schemes suggest that insufficient attention is paid to the shadow topic in instruction. Possibly this topic is regarded as too easy, and therefore is quickly passed over, or excluded from curricula, in high schools and colleges. The rich legacy of the shadow topic in the classic science and the ways of encompassing it effectively in learning materials can be exemplified in the textbook by Rogers (1960) where shadow is presented as a tool of a spectacular scientific inquiry.

Colour (scheme 8)

The abundance of the Colour-Pigment Scheme revives the old problem of the integrative approach in teaching science (premise P-6 above). Indeed, the assertion that a colour corresponds to a particular frequency in the electromagnetic spectrum cannot, by itself, adequately account for a variety of *observed* phenomena. For meaningful elaboration of colour perception, at least a simplified qualitative model must be introduced into the two complementary contexts of radiated and reflected light. Thus the trichromatic model of primary colours (Young-Helmholtz) and the simple rules of colours addition and subtraction based on it, are sufficient to account for many everyday experiences. Such a treatment does not presume sophisticated operations or tools (e.g. Mueller *et al*. 1966, Goldberg 1989). The facets of the Colour-Pigment Scheme reveal significant experience with pigments on the part of students and the ad hoc rules they invent to account for this experience. Some of the latter are reminiscent of the naive colour theory of Goethe (compare with Facet 8-8), a cultural rival of Newtonian optics. Goethe claimed that colour perception was a psychological phenomenon due to the eye's perception of the degree of brightness in a mixture of colourless light with darkness (Mason 1962, Mach 1926, Park 1997). These ideas did not seem foreign to our students who had not been instructed in colour theory. We learn that ignoring the colour topic altogether invites its interpretation by naive tools (Aristotle's `horror vacui' was rejected by physics, but the constructivist theory made it adequate in understanding people's knowledge at the time.)

An interesting and controversial picture emerges when one observes the type of instruction regarding colour usually delivered in high-school and college introductory courses. Textbooks for physics majors do not generally include colour as a topic (e.g. Resnik *et al.* 1992, Tipler 1990, Young 1992, Serway 1990). Among college and high school physics texts (and therefore curricula), some ignore the phenomenon of colours (e.g. Mulligan 1991, Cutnell and Johnson 1992) and others address only their *physical* meaning, i.e. as corresponding to different frequencies of electromagnetic waves (e.g. Giancoli 1995). Only a few textbooks at this level consider colour in relation to vision, as they appear to the observer in the two complementary settings of light sources and reflectors (e.g. Hewitt 1992). In contrast, instruction of non-science majors often includes a comprehensive coverage of the subject (e.g. Goldberg 1989, Faughn *et al.* 1991, Merken 1993). What causes this imbalance in favour of a population not specializing in science?

The variety of approaches to the presentation of the subject of colour reflects different views on physics courses in general. This is a domain where the role of the observer is crucial. Indeed, a genuine understanding of colour cannot be reached without involving knowledge about *how* we perceive colour (e.g. Gregory 1979, Williamson and Cummins 1983). Such knowledge might be seen as extending the boundaries of the subject. In contrast to mechanics, colour vision is subjective; for example colour identification is dependent on background, illumination etc. Moreover, in keeping with the model of spiral curriculum, involving a repetitious learning of the same topic at different ages (Bruner 1960), one may assert that instruction on colour in the middle school (e.g. Leyden *et al.* 1988) will be beneficial to the learner only if its further reinforced at the higher levels of education, in high school and college. An antithesis to the conservative approach of refraining from treatment of colour and vision can be found in the celebrated university physics course by Feynman (1964).

Some implications

The facets-scheme approach to students' knowledge implies that science educators should address, in the first place, the relevant schemes of students' knowledge elicited by research methods. It is necessary to challenge and confront schemes, whereas facets are multiple, context dependent and thus less fundamental. The existence of schemes of alternative knowledge in optics suggests further effort should be made to provide similar information regarding alternative conceptions in other areas (Pfund and Duit 1994).

Elicited optics schemes suggest that the observer's role in vision should be elaborated at the beginning of physics courses, thus addressing the Scheme of Spontaneous Vision by considering processes within the observer's eye.

An intensive discussion on the instrumental nature of light rays is required to challenge the Corporeal Light and Image Projection Schemes, both of which are based on erroneous conceptions of light rays. An instructional shift from light ray to light flux may facilitate challenging the extremely strong and versatile spontaneous knowledge held about light rays. To address the Image Holistic and Image Projection Schemes one should elaborate explicitly on the concept of the image in optics, presenting its possible versions through a comprehensive comparison between them. The introduction of the concept of light flux instead of exclusive reference to light rays and the use of qualitative problems challenging the elicited facets (Galili 1996), may encourage the refutation of the alternative conceptions of optical image and assimilation of the scientific one.

The knowledge of schemes identified in the context of pinholes, shadows and colour vision should encourage the reintroduction of these often underestimated topics in optics curricula, as a means of fostering a desirable conceptual change from the widely spread alternative knowledge of these topics.

Finally, there is a need to include, especially in the introductory curriculum, a minimal qualitative treatment of certain topics which are presently taught only in advanced courses. For instance, the influence of atmosphere (or other medium) on observed optical phenomena and some interdisciplinary content regarding the peculiarity of light-colour perception could well be introduced. The fact that these contents are complex should not be an excuse for their *total* rejection. Rather it should result in an effort to construct teaching materials in forms appropriate to the introductory course. Examples of the feasibility of this task are available (e.g. Hewitt 1992). The results of research (such as facets of knowledge and its schemes) may guide this effort.

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Appendix

The elicitation of facets was made at the first stage of data processing (figure A-1). At this stage similar explanatory propositions, response behaviour and strategies to cope with questions were identified as facets of knowledge. Contributions to a facet could come from responses to different questions which had in common a certain physical context (possible variations in wording were tolerable). The next step of analysis was the identification of clusters of facets sharing the same explanatory conception expressed in more general and abstract terms (less situation dependent).

The following coefficients were introduced to characterize the spreading of facets and schemes.

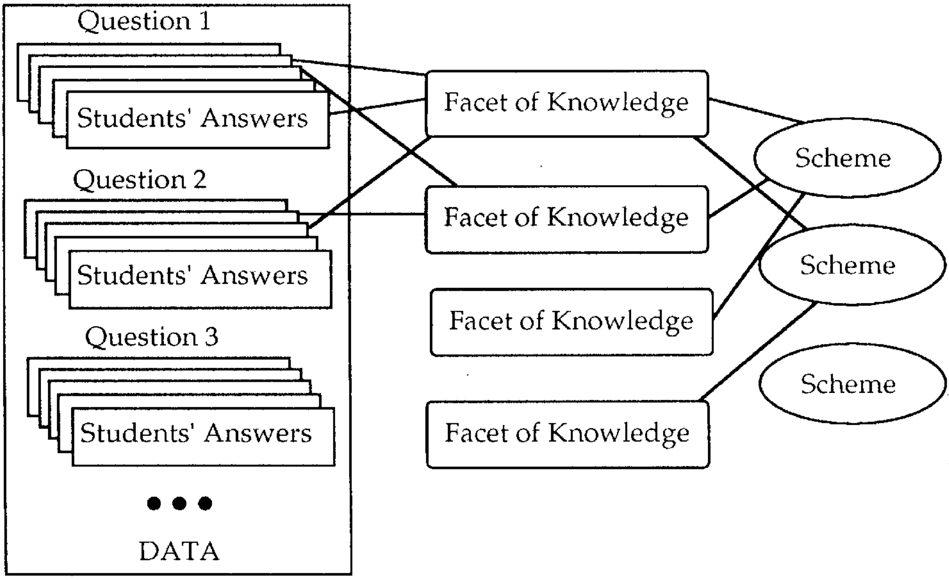

Figure A-1. Process of categorizing data toward its facets-scheme organization. Only representative connections are shown.

FA — Facet Abundance coefficient. The identification of facets is based on students' ways to address particular physical settings. When we collect contributions to a particular facet form the shown responses to the same question, the frequencies contribute to the FA as a sum. This is because in this case different propositions cannot originate in the same individual. However, when the contributions to the facet come from responses to different questions, one must average their percentages. For example, the following responses were given to *different* questions (with frequencies as shown):

- `The man sees by aiming his look (by gazing) at objects' (78%);
- `The man receives an order from his brain. This order passes to his eyes and activates his sight' (58%);
- `We see objects by our eyes which can see by sensing' (44%).

The facet (F1-2) was enunciated as: `In students' written descriptions and sketches describing the vision process, no reference is made to a *physical* relation between the observing eye and the observed objects'. FA (60) was calculated as the average of the frequencies.

FG - Facet Gain coefficient. This equals the difference in the abundance of each facet between the groups before (FA_1) and after (FA_2) instruciton. The flag parameter t was included to show whether the difference took place in the direction of knowledge improvement (positive result):

$FG = t(FA_2 - FA_1)$ [$t = +1$ for scientifically correct statement or strategy; otherwise, $t = -1$]

For example, for the facet: `A converging lens compels light rays to pass through its center and an inverted image is obtained' (Facet 5-1), $FA_1 = 5$ and $FA_2 = 45$, and $t = -1$ and hence $FG = -40$, indicating an undesirable difference.

SA — Scheme Abundance, represents the popularity of a scheme. It is determined by FA coefficients. As we were only interested in *group* differences, the answers were analysed per sample rather than per student. For this goal to evaluate the spreading of the scheme an average was taken of the FA's of the facets affiliated to the scheme. This step moderated our inferences regarding the abundance of a particular scheme.

SG — Scheme Gain coefficient was defined by $SG = SA_2 - SA_1$, by analogy with FG.