DOCUMENT RESUME

ED 390 636 SE 056 270

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TITLE	An Emphasis on Perception: Teaching Image Formation Using a Mechanistic Model of Vision.
SPONS AGENCY	Educational Testing Service, Los Angeles, Calif.
PUB DATE	Apr 95
NOTE	33p.; Paper presented at the Annual Meeting of the National Association for Research in Science Teaching (San Francisco, CA, April 1995).
PUB TYPE	Reports - Research/Technical (143) -- Speeches/Conference Papers (150)
EDRS PRICE	MF01/PC02 Plus Postage.
DESCRIPTORS	*Depth Perception; Geometry; *Light; Models; Observation; *Optics; Physics; Pretesting; Scientific Concepts; Secondary Education; *Vision; *Visual Discrimination; Visual Perception

ABSTRACT

An effective way to teach the concept of image is to give students a model of human vision which incorporates a simple mechanism of depth perception. In this study two almost identical versions of a curriculum in geometrical optics were created. One used a mechanistic, interpretive eye model, and in the other the eye was modeled as a passive, black-box receiver of light. These curricula were used with two treatment groups (N=28) of students from an ethnically diverse public school, which were balanced for gender, mathematics class completed, and self-reported grades in mathematics and science. It was concluded that the study demonstrated the gains to be made by teaching students a perception-based model of image formation rather than a more traditional geometrical definition of image formation. In particular, students who were taught a mechanistic model of visual perception exhibited a better understanding of the notoriously difficult relationship between an observer and a virtual image. They were also better able to identify the location of an image in a range of real-world optical situations, and were less likely to think of it as located on the surface of a mirror or lens. (JRH)

An Emphasis on Perception: Teaching Image Formation using a Mechanistic Model of Vision

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Presented at the annual meeting of the National Association for Research in Science Teaching, San Francisco, April 1995, as part of an interactive video-based discussion entitled "Three approaches to teaching optics."

This work was partially supported by the Educational Testing Service.

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Introduction

The principles of image formation, central to geometrical optics, are notoriously difficult for students to understand (e.g., Arons, 1990; Bendall, Goldberg & Galili, 1993; Galili, Bendall & Goldberg, 1993; Goldberg & McDermott, 1986, 1987; Hawkins, 1978; La Rosa et al, 1984; Pea et al, 1991). We would argue that many student difficulties arise because students have insufficient understanding of the human visual system. If, as Guesne's (1985) work has shown, students do not understand the relationship between light and vision, then they cannot appreciate the critical role of the human observer in image formation. Most instruction in geometrical optics gives little or no attention to the mechanisms of human vision.

This study[1] asks as its central question: For the purposes of understanding the concept *image* and its related properties, what is the nature of a good enough model of vision? For example, Guesne (1985) argues that an understanding of virtual image requires "the idea that an object is seen because of the light that comes from it and that penetrates our eye after having been propagated in a straight line in the intermediate space" (p. 30). According to her research, this idea is already quite an accomplishment for children; they do not acquire it until age 13 or older. But is this enough of a model to understand image formation? Or do students need more than light paths: a better model of perception that is clearly distinct from the paths of light rays?

We propose that a highly effective way to teach the concept *image* is to give students a model of human vision which incorporates a simple mechanism of depth perception. If students fully understand such a mechanism, we would expect them to be able to make specific inferences about what an observer would see, based only on the local pattern of rays striking the observer's eyes. Such inferences, we believe, lie at the heart of what it

[1] This paper reports on part of a larger study. For more details, see Allen (1994).

means to observe an aerial image, and may be used to operationally define the *image* concept itself.

Instructional Design Principles

Our principle hypothesis was that students would have a better understanding of the concept of *image* if they were taught to use a simple mechanistic model of visual perception, than if they were taught using a more traditional approach.

To test this hypothesis, we created two almost identical versions of a curriculum in geometrical optics. In one version ("Active Eye") a mechanistic, interpretive eye model is used throughout to define *image* and to reason about optical situations. In the other version, the eye is modeled as a passive, black-box receiver of light, and the process of image formation is treated as essentially independent of the presence of an observer. This latter version ("Passive Eye") embodies Guesne's central idea but lacks a runnable mechanism for perception.

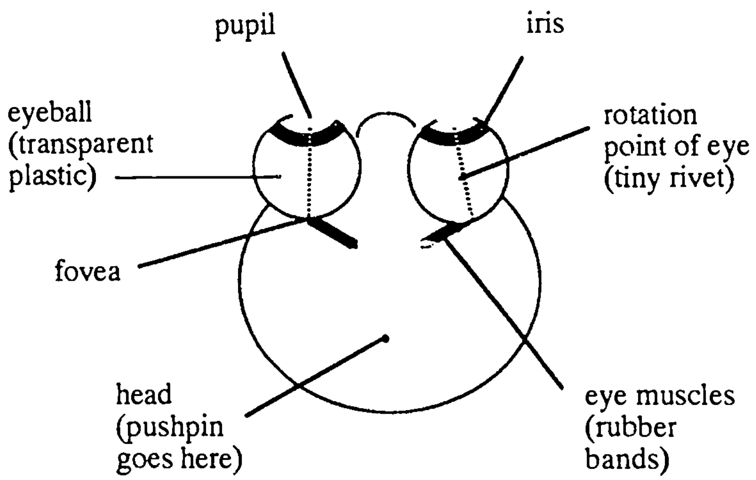
The "Active Eye" Model of Vision

We designed the "Active Eye" model of vision to explain how an observer can receive incoming light and interpret it as being from an object at a specific location. With such a model of vision, one can understand how certain patterns of light rays would give the same perceptual effect by fooling the interpretive mechanism. The perception literature suggests that in reality there is no single, simple mechanism for this interpretive process. There are several mechanisms which are known to contribute, including interposition, relative size, relative height, visual clarity, shadow detail, texture gradients, linear perspective, movement parallax, accommodation, convergence, and retinal disparity (Goldstein, 1989; Coren & Ward, 1989; Corsini, 1984).

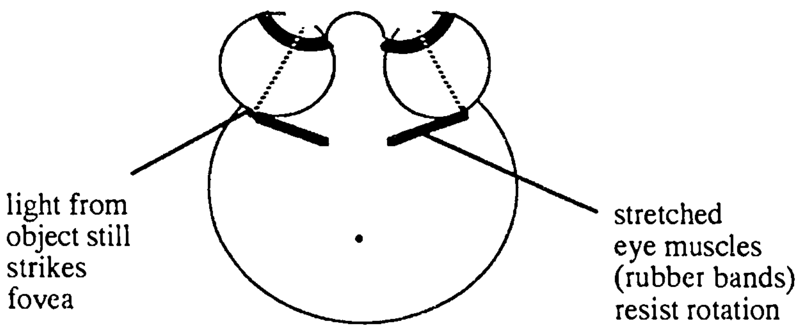
We chose a model of vision in which eyeball convergence is the principle cue for identifying the location of an object or image. In this model, the eyes point directly at whatever is being viewed, and the brain uses the kinesthetic feedback on the positions of the eyeballs in their sockets to determine the location of the object by triangulation. Although this is regarded as one of the less effective cues used in depth perception (e.g., Coren, 1989; Goldstein, 1980), it has the pedagogical advantage that it does not require the understanding of an inverted image created within the eyeball.

We embodied the model in a small plastic detector (called "the Plastic Person") with rotating eyes and eye muscles made of rubber bands.

The "Plastic Person"



(a) Plastic Person looking at a distant object: eyeballs are almost parallel, so eye muscles are hardly stretched.



(b) Plastic Person looking at a nearby object: eyeballs are highly rotated, stretching eye muscles.

Because the Plastic Person is literally transparent, light rays drawn on the underlying ray diagram can still be seen, followed into the pupils and finally traced to the back of the observer's eyes. This is designed to give students the impression of seeing the paths of light rays inside someone's head, and allows students to swivel the eyes so as to get the rays to "fall" on the foveas at the center of the back of each eye. The inclusion of the fovea constraint is necessary to ensure that the eyeballs are pointing exactly in the right direction, and it has the advantage of providing a neat model of peripheral vision in terms of incoming light rays striking a point on the retina that is outside the fovea.

In this model of vision, the Plastic Person has a runnable sequence of operations to carry out in order to see: 1) It must be positioned properly, facing roughly in the right direction. 2) Its eyes must be swiveled such that a light ray from the lens or mirror can enter the pupil of each eye, pass through the eyeball and strike the fovea at the center of the retina. This ensures that it is looking directly at something, not seeing it peripherally. 3) As a result of the swivel, its eye muscles (rubber bands) will be stretched to a greater or lesser extent. 4) The stretching of the eye muscles must be "interpreted" by its brain to determine the distance of the light source. The more the muscles are stretched, the closer it will think the light source is.

The step about the stretching of the eye muscles does not, at first glance, seem necessary. Instead, students could be given a model where the brain directly interprets the orientation of the eyeballs. This model is one of a series presented by diSessa (1981) and described as follows:

> Mathematically, those two directions from different standpoints toward a single object are sufficient to locate the object at their intersection point. In fact, your brain can do the calculation (roughly) to find out how far away an image is by sensing how 'pigeon-toed,' how much pointed inward from straight ahead your eyes are positioned to each aim directly at an object. (p. 5)

However, a crude model of eye muscles is included to give the students a runnable mechanism for the interpretive part of the visual process. Students can see, for example, that a person looking at an image in a plane mirror might interpret what she sees as an object behind the mirror *in the sense that* both situations provide the same amount of stretch to the eye muscles, and thus the same information to the brain. The model needs to have a mechanism for converting light input into a specific state of the visual system. Otherwise, students are likely to misunderstand the local nature of the step "the brain determines where the eyes are pointing" by tracing back the rays in real space to their physical origin, rather than their perceived origin. In addition, there is a second reason for using eye muscle-stretch as what the brain interprets. Students can feel such a stretch in their own eyes when they look at something very close to them, so such a mechanism is made plausible and even crudely calibrated in their lab experiments.

Overall, the sequence of steps helps clarify the eye's internal workings that enable the observer to make interpretations. It also provides students with a sequence of actions that can be completed in order to determine what an observer will see in any situation. It thus accounts for the main features of an image: its location, orientation, and size. The actions are all simple, and linked to one another in a mechanical sequence, which makes them easier to remember and envisage in the absence of the physical device.

The "Passive Eye" Model of Vision

As a comparison treatment, students were given the same curriculum, but without the use of a transparent, mechanistic detector to define *image*. Instead, an image was consistently defined in geometrical terms, as located where rays come to a point, extended in either direction if necessary:

Here is a general rule for finding the image of any point source O, like this one. Look at the pattern of rays that started at O, and follow them until they leave the mirror, or whatever has changed their direction. If these rays, extended in either direction, all meet each other at a single point., then at that point, there is an image of O.

This definition is general and concise, but it seems somewhat arbitrary in the absence of a mechanistic model of vision. The observer's role is presented as subsequent to, and independent of, the process of image formation. It is introduced as follows, in the context of a plane mirror:

But there is a question about where you'd need to be in order to see this image. ... You'd have to be in a place where light that creates this image will enter your eye. So, for example, you could be here - and I'm drawing a little symbol of an eye to represent a person looking in this direction. Or you could be here, or back here somewhere. In each case, light is going into your eye after it leaves the mirror.

Although this model lacks a runnable mechanism of depth perception, it still incorporates Guesne's (1985) central idea that an image is seen if and only if light from the image travels in a straight line through space and penetrates the observer's eye. The model is also consistent with most instruction as described by La Rosa et al. (1984): "Our approach to the teaching of optics ... tends to rely on the eye of the observer merely as a tool for observing" (p. 396). The Passive Eye instruction is actually somewhat better than traditional instruction in terms of consistency and generality: a single, general definition of *image* is explicitly given, and a movable observer is included in the discussion of every optical situation.

Design Principles Common to Both Groups

With the exception of the different eye treatments just described, the Active Eye and Passive Eye conditions were made to be identical. Instruction common to both was designed to be as effective as possible, within the pragmatic constraints of a 6-hour curriculum (excluding individual assessments).

Several design principles distinguished the instruction from traditional high school optics courses. These included the following:

- There was no formal mathematics at all, since the emphasis was on qualitative reasoning.
- Concepts such as "image" and "image size" were procedurally defined.
- Diagrams were less stylized than traditional ray diagrams: omitted were focal points, principal axes, and principal rays. Objects were drawn in arbitrary arrangements with respect to mirrors, and the mechanism of reflection was used throughout to determine the path of light striking any mirror. Both ends of an object were mapped to determine image size and orientation.
- Regular, non-luminous objects such as pencils and clothespins were used throughout.
- The use of screens to view real images was left to the very end of the course; the primary means of detecting an image was to view it directly.
- Only mirrors were discussed in detail (primarily due to time constraints).

Hypotheses

Our general hypothesis was that students who were taught to use the mechanistic model of visual perception (the Active Eye students) would have a deeper and more flexible understanding of *image* than those who were taught a more traditional, less interpretive model of vision (the Passive Eye students).

In particular, we expected that the Active Eye students would outperform the Passive Eye students in three areas of known student difficulty:

(A) Students often have great difficulty deciding where an the eye of an observer would have to be to see an aerial image. (e.g., Goldberg & Bendall, 1991; Goldberg & McDermott, 1986, 1987)

We expected Active Eye students to show better performance in this dimension because their model of visual perception could provide a robust and flexible way to interpret the proximal stimulus of light entering the observer's eyes, while minimizing the distractions of light paths elsewhere in the optical system.

(B) Students often have difficulty constructing and interpreting orthograhpic ray diagrams. (e.g. Galili et al., 1993; Goldberg & McDermott, 1987)

We expected that Active Eye students to have a better understanding of the semantics of orthographic ray diagrams, since they had a model which made a clear distinction between the paths of physical light rays and the interpretations of an observer.

(C) Students often have difficulty identifying where an image is located, just by looking at it. For example, they often report that the image created by a plane mirror is located on its surface. (e.g. Hawkins, 1978; Goldberg & McDermott, 1986)

We expected the Active Eye group to perform better than the Passive Eye group in determining where an image is located, because their model of a detector might give them both a conceptual advantage (in understanding why an image is not confined to a physical surface) and a heightened awareness of their own perceptual process when viewing an image.

Methods

The subjects for the study were 28 students from an ethnically diverse public school in the San Francisco Bay Area. Aged 14-15, they had not yet received any significant formal optics instruction. Across the two treatments, groups were balanced for gender, mathematics class just completed, and self-reported grades in mathematics and science. Students worked in pairs for the instructional part of the study (lasting approximately 3 days x 2 hours per day), but were assessed individually. The study took place in a laboratory setting, with one pair of students working at a time. The curriculum (excluding assessments) took approximately 6 hours to complete.

VIDEO SEGMENT 1: EXPLORING THE MODEL (ACTIVE EYE)

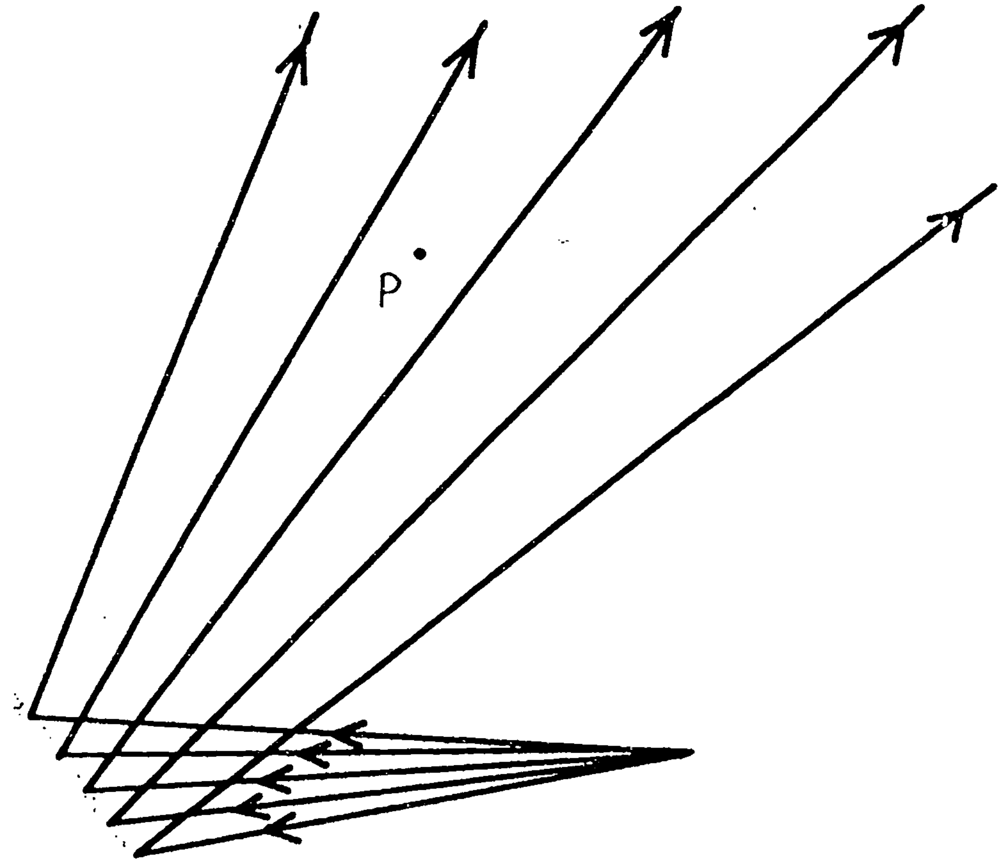
The following segment of video shows two Active Eye students (of average performance within the group) working as a pair during the instructional part of the course. The students have just learned the definition of an image using the Plastic Person in the context of a plane mirror, and are now doing an exercise (Exercise 13) in which they must apply that definition to several novel optical situations, all presented in diagram format. The situations are varied to include mirrors and lenses, but these are all treated as generic ray-redirecting devices, and drawn as generic yellow blobs. This was done to encourage students to focus on the more general properties of images, so that they could apply the same basic principles to both mirrors and lenses.

The students have in front of them the following written statement of the exercise:

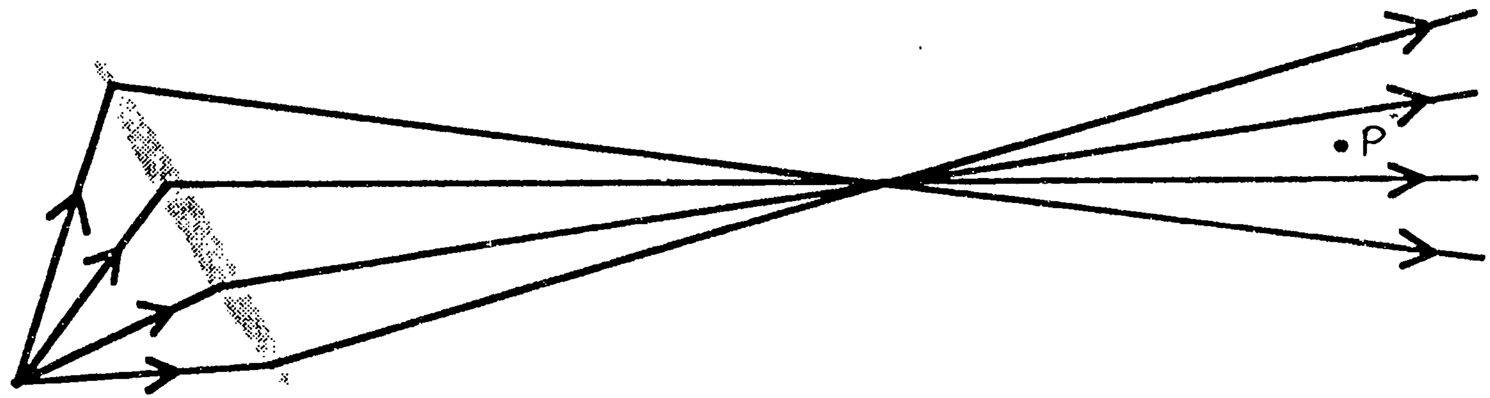
FXERCISE 13

- For each of the 3 diagrams, answer the following question:

The diagram shows a point source of blue light (such as the tip of a pencil), from which several light rays are shown. The rays strike some kind of mysterious yellow device (not necessarily a mirror) which bends or bounces them in unusual ways as shown. Where would the image appear, according to a person at the position shown? Label it on each diagram.



Exercises 13(a)



Exercise 13(c)

13

Transcript (B=blonde-haired student; D=dark-haired student)

(Diagram a)

B: Wow. Would it be...?

D: Would it be like right there? [traces two rays back correctly with finger]

B: Yeah, you'd just, you'd line ... [traces two rays to the same place with finger]

D: But would these guys come to a point? [traces all image rays back with finger]

B: You wouldn't do all of them; you'd just do two.

D: Well, each two has a different point.

B: I know, huh... Oh, it's this person [points to P]. I think this is the person, so he'd be over here, and so it'd be these two. [traces two rays back, on either side of P.]

D: Well do we... we use this little person then, don't we? Wouldn't we?

B: If you want to.

[D sticks person at P, and swivels eyeballs.]

B: There, and then we have to draw these...

[They pick up pens.]

D: [Handing blue marker] Here.

B: Red.

D: Why red?

B: ...[unclear]

[B extends two rays back correctly.]

B: Right here. [They each draw a dot at the image point.]

D: Put "I" for "image.

B: Yeah. Image of O. [writes "image of O."]

D: OK.

B: Oh wait, image of O?

D: There is no O!

B: I know [laughs].

[D erases "of O."]

D: Just image.

B: OK.

(Video jumps to Diagram c)

[B pushes plastic person in, and they both swivel the eyeballs.]

B: So he does his two outside lines and see what, it'd be right here [points to image.] That's really neat.

D: [Draws dot at image point.] That's where the image would appear to be.

B: So is that it, for that? Shall I push "play"?

D: Yeah.

Short commentary on the video segment:

[Explanatory note: The students' reference to point "O" arises because the previous exercises explored the case of a flat mirror, and one of the points on the object was labeled "O" to distinguish it from other object points. In this exercise, however, there is only one object point shown, and no label is provided.]

We feel that this piece of videotape shows students doing some excellent reasoning with the mechanistic model, and shows the power of the model in novel situations. The students successfully identify the location of the image seen by the person indicated, for both a mirror and a lens, (one virtual and one real image.)

The statement, "Well, each two has a different point," suggests that the students recognize that different observers have the potential to see different image locations. We regard this as a productive insight, especially valuable in cases where an image is not absolute in space, but varies its location with observer (see video segment 3). Further, the students know which rays are relevant to the particular observer shown.

In Diagram c (a real image created by a lens), the students again recognize which rays would reach the observer's eyes, and they make their deductions based on these rays. The comment, "That's really neat," suggests that the model makes sense to that student, and even that it provides some explanatory usefulness.

Finally, it is interesting that the students choose to go through the steps (1-4) of the runnable model for each diagram, even though their early finger-tracings indicate that they may also able to do a short-hand version of the reasoning, without the Plastic Person being present.

Assessments and Results

The pre- and post-tests assessed students on their understanding and use of the concept *image*, both in the real world and in a diagrammatic context. All questions were open-ended performance assessments and required some interpretation in grading. In addition, many questions had multiple parts or required the students to do several different types of reasoning.

Students' performances were scored based on 7 dimensions representing areas of traditional student difficulty, as reported in the literature. These were: (A) difficulty deciding where the eye of an observer must be to see an aerial image; (B) difficulty using an orthographic diagram to explain image formation; (C) belief that the image is located on a mirror's surface; (D) reluctance to choose an orthographic representation when drawing an optical situation; (E) difficulty understanding the idea of point-to-point mapping and multiple rays; (F) difficulty understanding the concept of *virtual image*; and (G) poor understanding of the role of light in vision. Every question was broken into one or more "items", each of which provided an opportunity for demonstrating competence in one of the seven areas of difficulty. In all, there were 48 such items. Care was taken to ensure that the different items in each question were independent of each other; that is, they involved responses to different parts of the question. Each item then had a scoring rubric designed for it, and a corresponding score of 0-2 was assigned to each subject's performance.

ANOVA's carried out on students' scores revealed that both groups of students showed significant learning following instruction, and that this effect was broadly distributed across the dimensions of difficulty.

The Active Eye students significantly outperformed the Passive Eye students in two dimensions of their performance:

(i) Difficulty (A): positioning of observer

Over a range of optical situations, Active Eye students outperformed Passive Eye students in identifying the critical relationship between where an observer stands and what she sees, $F(1,27) = 5.02, p = .04$. Specifically, the situations where this difference appeared are "virtual image" situations, in which an image is not located at an obvious crossing point of rays. These included cases where (i) the image is virtual and no such crossing point exists; (ii) the rays are hidden from view in a mysterious box, or (iii) the rays form an ill-defined crossing region, where image location depends on precisely where the observer stands. It is interesting that Case i situations are those that are notoriously difficult for students to understand, and that Cases ii and iii are so difficult as to be omitted from all but the most ambitious high school curricula. It seems that the detector-based model of image formation gave students a robust method of interpreting diagrams of this type, without being distracted by the global geometry of light paths through the system.

(ii) Difficulty (C): identifying image location

Active Eye students were significantly better at identifying the location of a real-world image (either familiar or novel) by viewing it directly, $F(1,27) = 5.86, p = 0.03$. At least two aspects of instruction may have been responsible for the Active Eye students' better performance.

First, the explicit detector model may have given Active Eye students a deeper understanding of how local information determines what interpretations can be made, and thus helped them understand why an image is not restricted to the physical surface of a mirror or lens. Evidence for this conceptual component of learning comes from the result that fewer Active Eye students than Passive Eye students identified the location of an aerial image as on the surface of a mirror or lens. Second, Active Eye students may have gained a heightened awareness of their own eyeball convergence from learning the model, watching their partner's eyes move (Exercises 11 and 12), and attending to their own shifting eyeballs in the familiar context of a plane mirror (Exercise 12). Evidence for this depth-perception component of learning comes from the result that, of the students who identified an image as not confined to the surface, a larger fraction of Active Eye students were able to correctly identify the image location as in front of (or behind) the mirror (or lens). Either of these possibilities -- and they may well be interlinked -- suggests an advantage to using a detector to model visual perception.

The significance of better performance in Dimension F should not be underestimated. If understanding the concept of *image* relies on an understanding of a perceptual process, then a student who "sees" an image is on the surface of an optical device faces a severe disadvantage. Similarly, a student who can accurately perceive an image as in front of or behind an optical device is in a much better position to appreciate the ray diagram as an explanation of this perception.

VIDEO SEGMENT 2: ASSESSMENT Q6 (ACTIVE EYE)

In this segment, the blonde-haired student answers assessment Q6, which has 2 parts, (a) and (b):

QUESTION 6 (DIAGRAM INTERPRETATION)

- Here are some diagrams. Each shows a person (standing at position "P") looking into a mysterious box. On the right is a point source of red light, such as the end of a pencil. As you can see, whatever is in the box changes the pattern of light rays from the source. I'd like you to tell me what (if anything) person P would see in each case .

Transcript:

Question 6(a):

B: Well, um, I was just wondering, you know that little guy with the eyes, can you make bigger ones?

Exp: Um,.. suppose you could, what do you think? Suppose you could make..

B: Well then you could make him to fit this, couldn't you?

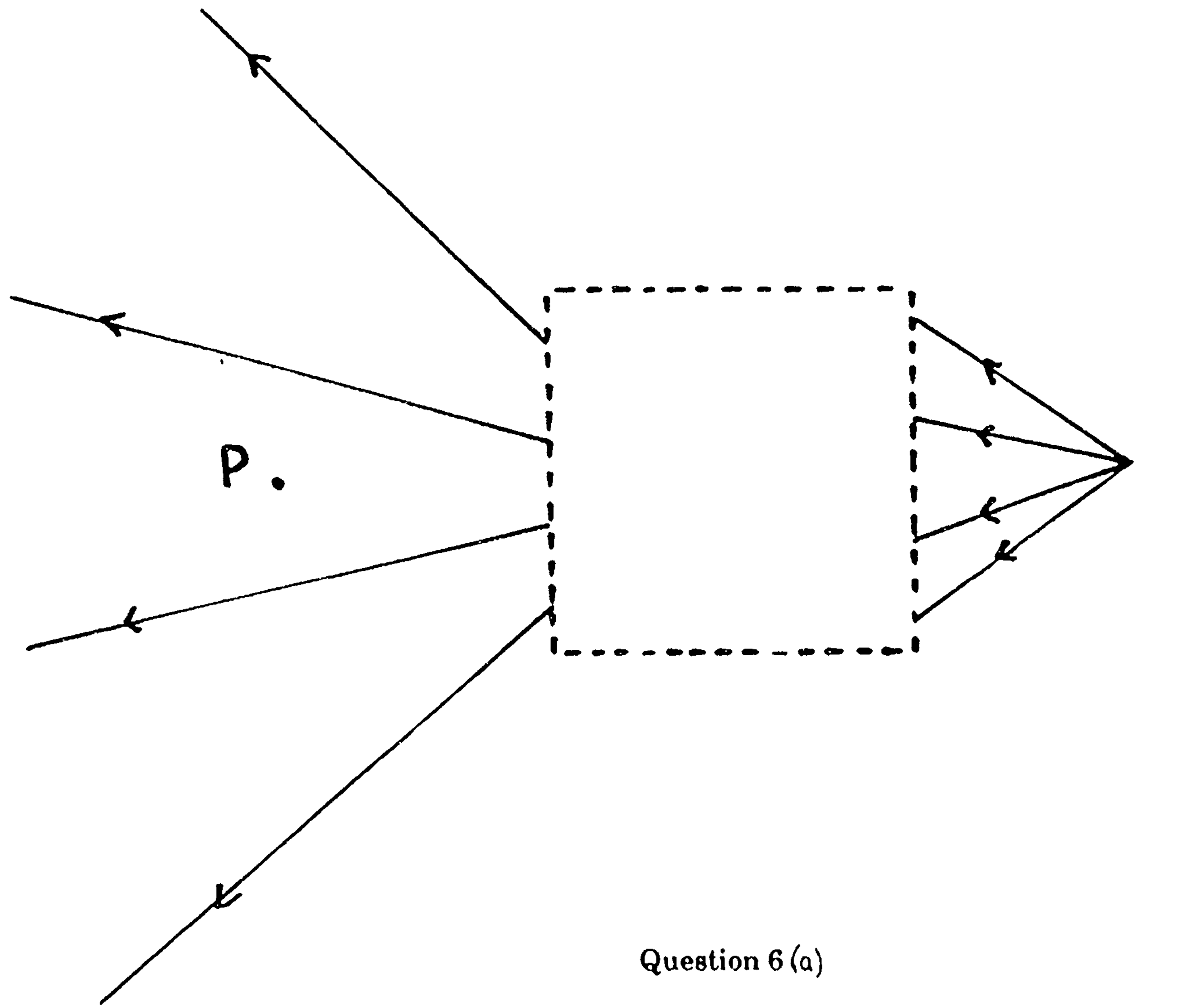
Exp: Oh, OK, so tell me about that then, suppose you could do that.

B: Well then [traces two rays back] he'd see something that was in the box; he'd see that there was light coming from in the box; he'd see something in here.

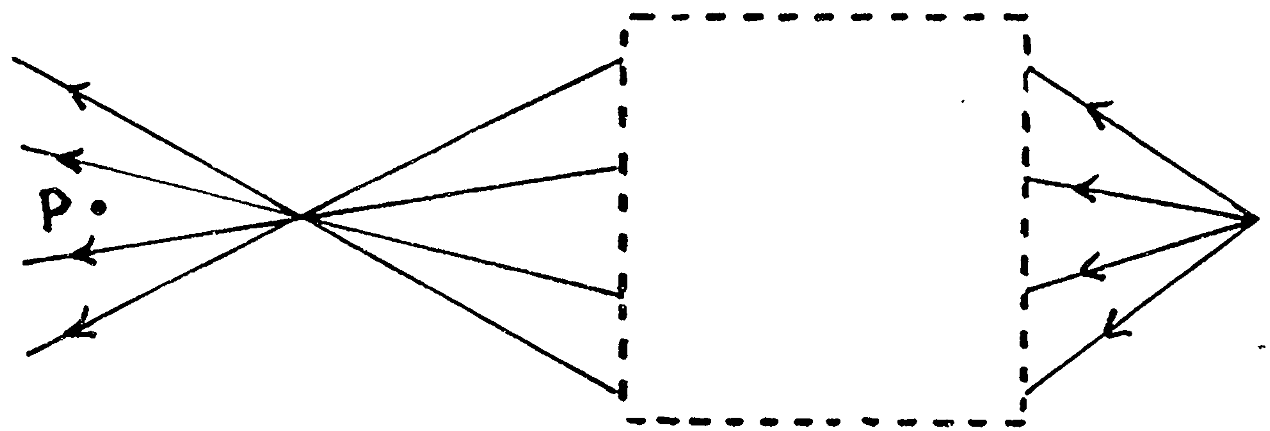
Exp: OK, would you be able to just draw that maybe on the sheet, show me what you're saying he would see?

B: Well, just, ... shall I draw it <u>on</u> here?

Exp: Yeah, that's why I put the plastic on, so you could draw on those.



Question 6 (a)



Question 6(b)

B: I need a ruler. [gets ruler, correctly extends two rays back] He'd see something right here.

Exp: What would he see?

B: Um, light, a point of light coming from there?

Exp: And why would that be? Why would he see that?

B: Because he'd join the two rays of light that were going to his eyes - if you could make him bigger - and he'd join them, and he'd see something here.

Exp: OK.

B: Should I go on to the next one?

Exp: Yeah.

Question 6(b):

B: He'd see something here. [image]

Exp: What would he see there?

B: Um, the source of light, the light, or the - whatever is making the light, like a pencil or something I think. Yeah. He'd see it here [image].

Exp: OK. And that's because?

B: Because he'd get the rays and then he'd join them with his eyes, and that would be right here.

Exp: OK.

Short commentary on the video segment:

This question is particularly difficult because the optical device that changes the rays is invisible. We find it impressive that the student is able to swiftly and correctly deal with both situations, without needing to know or even speculate on the contents of the "mystery box." (This is in sharp contrast with most Passive Eye students, who apparently felt a need to visualize entire ray paths.)

From her finger tracing and her language, it is clear that she is using the model in its two major phases: tracing light paths into the person's eyes, followed by tracing lines of interpretation away. (e.g., " Because he'd get the rays and then he'd join them with his eyes...")

It is interesting that the student proposes building a larger person, rather than drawing more rays. Perhaps the mysterious nature of the box discourages her from drawing in more rays; students were accustomed to adding rays in situations where they could complete them using reflection from a mirror.

VIDEO SEGMENT 3: ASSESSMENT Q9 (ACTIVE EYE)

In this segment, the dark-haired student answers assessment Q9, which has 3 parts, (a), (b) and (c).

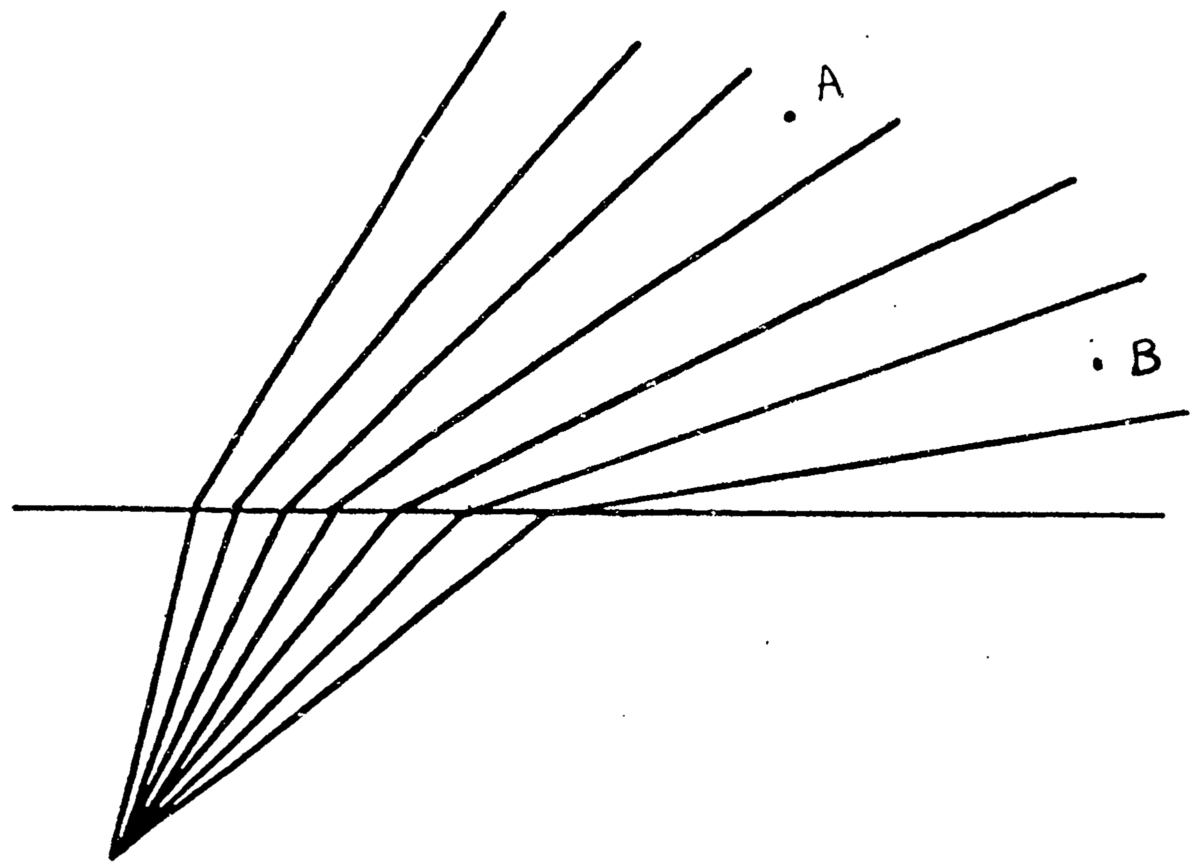
QUESTION 9 (DIAGRAM INTERPRETATION)

The diagram shows rays of light bending at a single surface.

(a) Suppose the diagram represents you sitting in the bathtub, looking at your submerged big toe. On the diagram, draw where your toe would be. Also label the water and the air.

(b) Suppose your head is at A. Where would your toe appear to be?

(c) Now suppose you were to move your head to B, closer to the surface of the water. Would your toe still appear to be in the same place? Explain.



Question 9

Transcript:

(Beginning after she has already located the toe, water and air, and has done the correct diagrammatic constructions...)

D: Do you want me to explain why it wouldn't appear in the same place? [laughs] Um, it wouldn't appear in the same place, because the point that you're looking at it from is different, so it, it makes your viewpoint different. Like with the pen in front of the mirror, the image wouldn't appear to be in the same place if you moved and looked at it diagonally instead of straight. Um, ...

Exp: So how did you figure out where it was in each case?

D: Well I imagined that there was a person right there (B) and the rays of light were going into their eyes, and I just connected the two lines. Oops, well maybe I should just do those two [corrects mistake]. Well, [laughs] I did the wrong ones over here. I think the image is right there instead of over here.

Exp: Just put a big arrow from outside saying "this it it". So just put a big arrow in, just to point to that point - yeah, that's great - and I'll know that's where you mean.

D: OK.

Exp: OK. And how did you decide that the toe was there; why did you think that? The actual toe - you've labeled "toe" there.

D: Um, because that's where the, [laughs] that's where the rays of light are coming from.

Short commentary on the video segment:

Up until this point, the students have never previously encountered a case of single-surface refraction, have not studied lenses in detail, and have not seen a case of an image in a non-absolute location. The student answers this question correctly, in spite of the fact that it concerns an extremely difficult optical situation - one that is seldom, if ever, addressed in physics textbooks.

It is interesting that the student does not believe in images as things that are absolute in space, even in the case of a plane mirror ("Like with the pen in front of the mirror, the image wouldn't appear to be in the same place if you moved...") This is a case of a "misconception" that we argue is actually productive rather than hindering students' understanding. If, as we believe, the image is a perceptual phenomenon, then there is no compelling general reason for it to have the same location as perceived by different observers.

Like the previous student, this student reasons successfully with the two principle phases of the model (loosely speaking: light into the eyes, then interpretation out). She says, " I imagined that there was a person right there (B) and the rays of light were going into their eyes, and I just connected the two lines."

The student's self-correction shows that she is able to identify which rays in a diagram determine what an observer sees: viz, rays entering his or her own eyes.

Conclusion

This study has demonstrated the gains to be made by teaching students a perception-based model of image formation rather than a more traditional geometrical definition of image formation. In particular, students who were taught a mechanistic model of visual perception exhibited a better understanding of the notoriously difficult relationship between an observer and a virtual image. They were also better able to identify the location of an image in a range of real-world optical situations, and were less likely to think of it as located on the surface of a mirror or lens.

Broader significance to other domains

The principles behind the design of the Plastic Person detector may be applied to other domains of physical science where students often experience difficulty in learning central concepts.

For example, it is well known that students have difficulty distinguishing the extensive concept of internal energy (sometimes called "heat" or "heat energy") from the intensive concept of temperature (e.g., Lewis, 1987; Linn & Songer, 1991; Linn, Songer, Lewis & Stern, 1990; Wiser & Kipman, 1988). These concepts might be easier to discriminate if students had a simple mechanistic model of a thermometer as a local measurement device that could not possibly "know" what is happening in the rest of a large body. Pedagogically, the situation is analogous to learning about image formation. In the case of optics, students may look with a holistic viewpoint at light paths through an optical system, but the concept of *image* is predicated on the local viewpoint of the Plastic Person detector. Similarly, students may look with a holistic viewpoint at the distribution of matter and internal energy in a system, but the thermometer is limited by the nature of its input (kinetic energy of molecules striking its surface) to making a local interpretation of this larger world. This limited perspective makes it possible to define the concept of *temperature*.

Many other concepts in physical science have the property that they describe only a local interpretation of a global situation. For example:

- Phase velocity is a local interpretation of a wave train moving through space.
- Instantaneous acceleration is a local aspect of a velocity-time graph.
- Simultaneity is a local interpretation of events in a space-time continuum.
- Electric field is a local aspect of a distribution of charges.

Such concepts present a challenge to learners because they require transitions between multiple perspectives. At the global level, students need to be able to represent and reason about a physical phenomenon such as light travel or heat flow; at the local level, students need to be able to interpret aspects of these phenomena to identify concepts such as *image* or *temperature*. This research study suggests that mechanistic models of detectors might help students to understand such concepts, using simple local mechanisms where the students can imagine themselves as the detector and ask "What would I think is happening?"

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