GALIT BOTZER AND MIRIAM REINER

CHAPTER 8
IMAGERY IN PHYSICS LEARNING - FROM PHYSICISTS' PRACTICE TO NAIVE STUDENTS' UNDERSTANDING

Department of Education in Science and Technology Technion, Haifa, Israel

Abstract: The main issue in this chapter is imagery in physics learning. Three epistemological resources are used to address this issue: Imagery in the history of physics, cognitive science aspects of imagery, and educational research on physics learning with pictorial representations. A double analysis is used. The first analysis is focused on imagery in classical test cases in the history of physics, such as Faraday's work on magnetism and Einstein's thought experiments described in the 1905 papers. The categories identified in the first analysis were used for the second: analysis of imagery in naive students' reasoning. In particular we describe a learning experiment, which examined naive students' representations of magnetic phenomena, during hands-on activities in the physics laboratory. We show that naive students use imagery in making sense of the physical phenomena; that modes of naive students' imagery resemble, on several levels cognitive mechanisms identified in physicists' imagery strategies; and that the product of imagery, pictorial representations, mirror processes of changes in conceptual understanding. We conclude with suggestions and implications for physics learning.

INTRODUCTION

Physics practice often involves cognitive processes such as mental simulations (Clement and Monagham 1999; Clement 1994) mental animations (Hegarty 1992) and thought experiments (Reiner 2000; Gilbert and Reiner 2000; Reiner and Gilbert 2000; Reiner 1998). All of these, require a form of 'seeing with the mind's eye', visualizing an event, mentally exploring a diagram, or comparing pictorial mental representations, i.e. thinking in pictures. Thinking by generating or manipulating pictures is termed here mental imagery or visualization. Mental imagery is used to make sense of physical experience and interact with the physical environment (Johnson 1987). For example, a child can visualize the trajectory of a moving ball and reach the hands to catch it without using any symbolic formalism. **How imagery relates to physics practice and to physics learning** is the focus of this chapter. We draw on three epistemological resources: Imagery in the history of physics, cognitive science aspects of imagery, and educational research on physics learning with pictorial representations.

The history of physics provides many examples in which physicists' used imagery to achieve scientific breakthroughs: Einstein claimed to achieve his insight

John K. Gilbert (ed.), Visualization in Science Education, 147–168.

into the nature of space and time by means of thought (Gendaken) experiments on mentally visualized systems of light wave and idealized physical bodies (clocks, rulers), in state of relative motion (Holton and Brush 2001; Miller 2000; Shepard 1988; Miller 1987). Another example is Michael Faraday's analysis of electromagnetic fields in terms of field lines (Holton and Brush 2001; Nerssesian 1995 Shepard 1988). The field lines are not only scaffolds, used to construct mathematical formalism, but also an integral part of electromagnetism, which serve as communication tool within the scientific community.

Research in cognitive science suggests that imagery and visual perception are, in many respects, functionally equivalent processes (Richardson 1999; Finke and Shepard 1986). The term 'mental imagery' refers to the ability to generate mental images and to manipulate these images in the mind (Kosslyn 1994). Empirical research shows that mental images could be scanned (Kosslyn 1994) or rotated in a measurable speed (Shepard 1996; Shepard 1988). Imagery is claimed to facilitate performance on a variety of visual tasks (Marks 1990; Finke and Shepard 1986) and in memory tasks (Clark and Paivio 1991; Paivio 1971). Imagery may also participate in cognitive problem solving (Richardson 1999; Kaufmann 1990).

Educational Researchers in physics learning examine the role of pictorial representations from three main perspectives: the first perspective focuses on learning environments, which use static or dynamic pictorial representations (e.g. Clement and Monagham 2000; Mayer et al 1996; Hegarty 1992; Reiner 1998). These studies indicate that pictorial representations and dynamic simulation are effective for conceptualization and problem solving in physics. The second perspective focuses on classification of pictorial and verbal representations, constructed by students for a variety of physical phenomena (Borges and Gilbert 1998; Driver et al 1994). These representations might reflect mental models held and used by students and hence might serve as evaluation tools. The third perspective focuses on cognitive mechanisms, which underlie construction of pictorial representations of physical phenomena. Reiner (1997) has shown that students communicated with each other through pictorial representations in order to construct meaning to electromagnetic phenomena. Clement (1994) analyzed the use of physical intuition and imagistic simulation in expert problem solving and claimed that these processes played an essential role in expert's thought.

The three epistemological resources, mentioned above, are closely related to each other. Students' ideas are, to some extent, parallel to the historical development of those concepts in science (Nerssesian 1995; Gilbert and Zylbersztajn 1985). Hence, we claim that physicists' practices are relevant to understanding processes of naive students' learning. This claim is also supported by current views, which perceive science learning as developing familiarity with the practices of knowledge construction within the scientific community (Lave and Wenger 1991). Cognitive science provides a framework for interpretation of scientists' imagery thought through the history of physics (Miller 2000; Shepard 1996), as well as interpretation of naive students' representations (Reiner 1997; Borges and Gilbert 1998).

Outline of this chapter

The chapter evolves in four parts. The first part provides a *theoretical framework* for analyzing imagery processes, based on the history of physics, cognitive science and educational research. The second part describes *a learning experiment,* designed to explore students' pictorial representations of magnetic phenomena. Results and *analysis of representations of magnetic phenomena* is the focus of the third. We conclude by discussing *the role of pictorial representations in physics learning* and show that naive students build representations, which are to some extent compatible with physicists' representations.

THEORETICAL OVERVIEW

Physicists' practice and imagery

Mental imagery and thought experiments are recognized as central epistemological mechanisms in innovation in physics (Miller 2000; Reiner and Gilbert 2000; Shepard 1988; Holton 1978). Galileo Galilee's theory is based on the extremely counterintuitive assumption that all bodies fall in a vacuum with the same acceleration, regardless of their weight. Galileo reached this conclusion through thought experiments. The term 'thought experiment' refers to scientists' performance of experiments in their "mind's eye". These experiments are run on idealized apparatuses and so require a high degree of abstraction (Miller 2000). Another example is Einstein's railway thought experiment, through which he established the idea of simultaneity in different frame of reference (Einstein 1922). Reiner (2000) identifies a typical structure of thought experiments and that consists of five components: an imaginary world, a problem, an experiment, experimental 'results' and conclusion. The abstraction level of Einstein's thought experiments is much higher then those of Galileo (Miller 2000) but both of them were catalysts to major breakthrough in the history of physics. Reiner (2000) claims that although these experiments are different in their goal, content, context and conceptual framework, they share the same structure. Other physicists such as Newton, Helmholtz, Bohr, Heisenberg and Feynman used the same structure of visual thought (Miller 2000; Shepard 1988; Miller 1987; Holton 1978). In particular many discoveries in electromagnetism are based on visual thinking.

Imagery in electromagnetism

Imagery has an essential role in the development of the electromagnetic theory. For example in the book 'De Magnete' (1600), the scientist William Gilbert concluded that the earth is a huge magnet, by using a visual analogy between a magnetic needle's incline near a spherical magnet and a compass needle's incline (Agasi 1968). Another example is the microscopic model of magnetic substance, suggested by the French physicist Ampere. Ampere (1820) suggested a microscopic model that contains small closed circuits inside a magnetized substance, by using an analogy to macroscopic current in a circular wire (Agasi 1968). A major contribution to the electromagnetic theory was made Faraday and Maxwell.

Michael Faraday's capability of visual imagination lead him to the invention of the term *field lines* and to the discovery of the electromagnetic induction (Holton and Brush 2001; MacDonald 1965). In 1821 Faraday repeated Oersted's experiment and placed a compass around a current-carrying wire. Faraday realized that the force exerted by the current on the magnet was circular in nature. He represented this phenomenon by a set of concentric circular line of force, so that a magnetic pole that is free to move experiences a push in a circular path around a fixed conducting wire. The collection of these lines of force is called the magnetic field (Holton and Brush 2001). Armed with this line-of-force picture for understanding electric and magnetic fields, Faraday joined in the search for a way of producing currents by magnetism. The idea of the line of force suggested to him the possibility that a current in one wire ought to be able to induce a current in a nearby wire, through an action of the magnetic lines of force in the space around the first current. Faraday examined this possibility trough many experiments in which he refined his experimental system (figure 1) and finally came to the conclusion that changing lines of magnetic force cause a current in a wire.

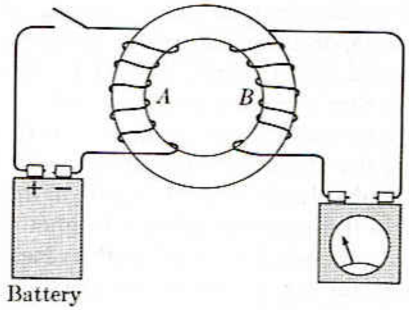


Figure 1*: Faraday electromagnetic induction experiment*

James Clark Maxwell (1860) work on electromagnetic waves was influenced by Faraday's work. In his book "*A Treatise on Electricity and Magnetism*" he describes Faraday's work:

> '…Faraday in his mind's eye saw lines of force traversing all space where the mathematicians centers of force attracting at a distance, faraday saw a medium where they saw nothing but distance: Faraday sought the seat of the phenomena in real actions going in the medium, they were satisfied that they had found it in a power of action at a distance impressed on the electric fluids.' (Maxwell, 1954 p. ix)

Nerssesian (1995) shows that Maxwell used Faraday's visual models and refined them through successive thought experiments. Maxwell developed his electromagnetic equations not by a chain of logical steps but by a series of increasingly abstract hydrodynamic and mechanical models (Shepard 1988). Maxwell considered what happens when an electric current oscillates along a straight piece of wire or circulates in a wire loop. To visualize the interactions between electric currents and magnetic fields, he constructed a mechanical model in which electromagnetic fields where represented by vortices bearing-ball and fluid (figure 2). In this model magnetic fields were represented by rotating vortices in a fluid and charges were represented by tiny spheres-like ball bearing, whose function is to transmit the rotation from one vortex to its' neighbours (Holton and Brush 2001; Miller 2000; Nerssesian 1995).

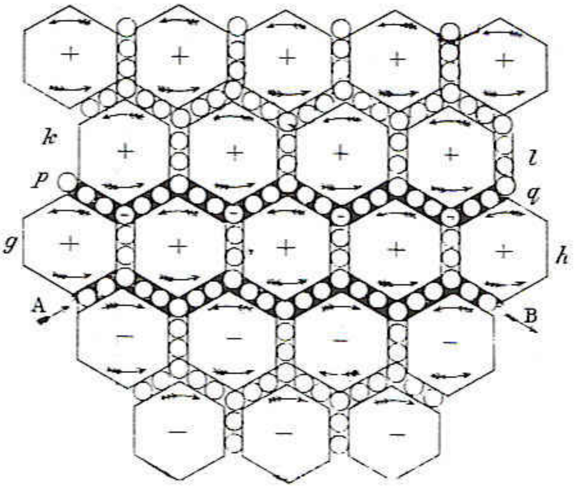


Figure 2: *Maxwell's vortices-ball bearing model of electromagnetic field*

This model allowed Maxwell to generalize the ideas of Oersted, Ampere, and Faraday so that they applied to electromagnetic interactions in a region of space where no current-carrying wire is present. He postulated that such regions contain charges (the ball bearing) that can be moved, or displaced, by changes in the magnetic fields (the vortices). The vortex-ball bearing model suggested that just as a varying magnetic field could generate an electric current in a wire (Faraday's electromagnetic induction), it could also produce a motion of a charge in space. This displacement current then produces a magnetic field (Oersted's effect). That field can then displace other charges, producing more displacement current (Holton and Brush 2001). Maxwell's theoretical conclusion, based on this mode, was that an electric current in a wire must send energy out trough space in a form of magnetic and electric fields. This energy is radiated away from the electric current and spreads out, wavelike in all directions. Maxwell formulated this conclusion in a set of four equations and then abandoned the visual model as if it was a scaffold for a building (Shepard 1988).

The effectiveness of mental imagery

The effectiveness of nonverbal processes of mental imagery is discussed in the context of creative thought in science (Miller 2000; Shepard 1988; Holton 1978) and in the context of problem solving in general (Richardson 1999; Shepard 1996; Clark and Paivio 1991; Kaufmann 1990). Shepard (1988) suggests that the effectiveness of mental imagery relates to four features of these processes: their private nature, their richly concrete and isomorphic structure, their engagement of innate mechanism of spatial intuition and their direct emotional impact. The private nature of imagery process and their departure from traditional verbal thinking explain their contribution to construction of novel ideas. The richness of concrete imagery, together with its isomorphic relation to the external objects, and events that it represents, may permit noticing of significant details that are not adequately preserved in a purely verbal formulation (Miller 2000). The spatial character of visual images makes them accessible to the use of spatial intuition and manipulation that have developed trough sensory interaction with the physical environment (Shepard 1996; Johnson 1987). Finally, vivid mental images provide psychologically more effective substitutes then do verbal encoding for the corresponding external objects and events. Is mental imagery effective for physics learning as well? We claim that it might be. Imagery is claimed to facilitate performance on a variety of visual tasks (Marks 1990; Finke and Shepard 1986) and in memory tasks (Clark and Paivio 1991; Paivio 1971). Imagery may also be part of cognitive problem solving, at list in the early stages of abstraction (Richardson 1999; Kaufmann 1990). Educational researchers suggest that pictorial representations and dynamic simulation are effective in conceptualization and problem solving in physics (e.g. Clement and Monagham 2000; Reiner 1997).

Mental-imagery modes

Miller (Miller 2000;1987) suggests a pattern that relates major breakthrough in physics in the 20th century to transformation of modes of mental imagery. Miller draws a timeline on which he places major discoveries in physics (figure 3). The horizontal axis indicates increasing time and increasing abstraction of intuition.

Galileo, Newton and Einstein's mental images were constructed trough abstraction of sensory experiences. The discovery of the electron in the early years of the 20th century lead to a new mode of imagery which was derived from pure imaginary entities. No one has seen an atom or an electron. Yet Bohr manipulated these entities to ensure the stability of the atom, which was modelled as a mini-scale solar system. He suggested a counterintuitive idea of "allowed orbits" and postulated a lowest allowed orbit below which atomic electrons cannot drop (Miller 2000). Bohr's model could not provide satisfactory explanation for discoveries and disagreements in the 20th and hence visualization was abandoned to be replaced by nonvisualizable mathematical formalism. In 1925 visualization was regain by

Heisenberg who derived the uncertainty principle from quantum equations that describe an electron's motion, by imaging himself measuring quantitative variables (Miller 1987). Following Miller’s description of development of imagery modes in the history of physics, we use three modes of mental imagery to analyze visual representations in physics.

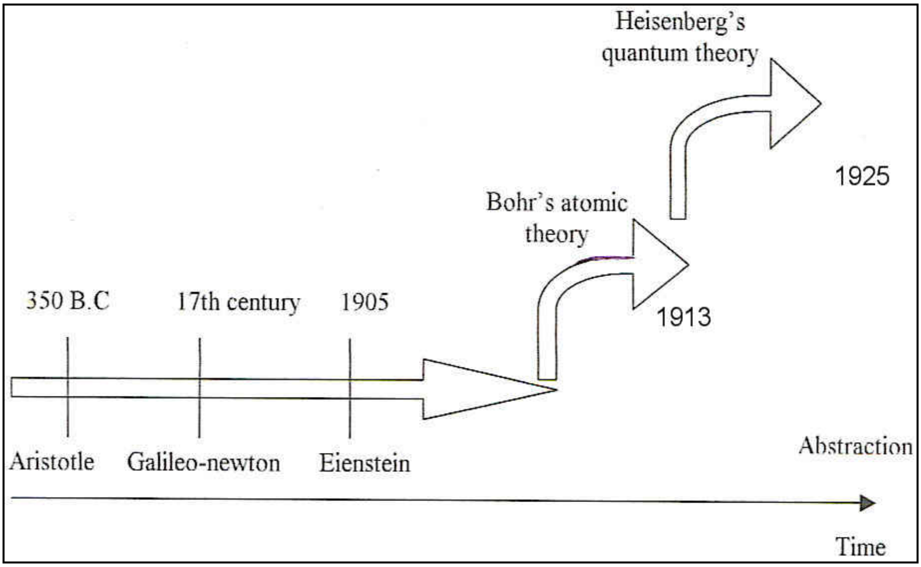


Figure 3*: Development of imagery modes throughout the history of physics*
(Miller A. I. (2000) Insight of Genius Imagery and Creativity in Science and Art, MIT Press)

Sensory-based representation refers to any image, derived from visual sensory experience. Pure imaginary representation– refers to any image which represents a situation which cannot be perceived through the senses. Formalism-based representation- refers to any image, based on mathematical formalism or formal rules.

In order to clarify each of the above imagery modes, we bring physics reasoning examples from the history of physics in table 1.

Table 1: imagery modes and examples from the history of physics

Modes of representations of physical phenomena	*Examples of Discoveries in Physics*
Sensory based representations	**Galileo** showed that all bodies fall at the same speed using a thought experiment that was based on concrete objects. (Reiner 2000)
Pure imaginary representations	**Boyle** visualized air-particles as tiny springs to explain the compression of the air (Agasi 1968). **Millikan** interpreted the experiment in which he measured the charge of the electron by imagining electrons 'riding' on drops of oil (Holton 1978).
Formalism-based representations	**Dalton** suggested a model, which represented atomic particles as wrapped with a fluid called 'caloric'. Based on Newton's inverse square law, he further assumed that particles should be pushed away from each other. (Agasi 1968)

We suggest that Miller's three modes of imagery might serve as a tool to analyze visual representations in physics learning. For instance, representations of magnetic phenomena can be classified according to the above three modes (see figure 4): a representation derived from the lines of iron-filling round a magnet, is a sensory-based representation; a representation derived from a microscopic model is pure imagery representation (no one really saw a microscopic magnetic dipole); and finally a representation, derived from field lines is a formalism based representation.

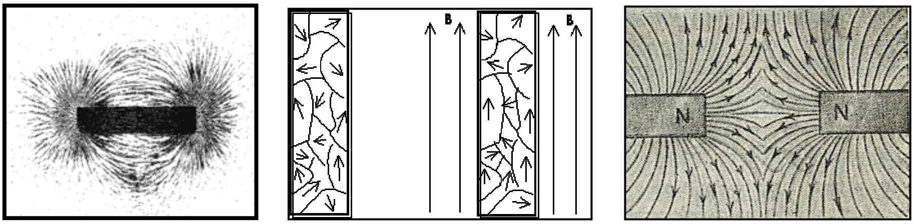


Figure 4*: Representations of magnetic phenomena: Sensory-based, pure-imagery and formalism based*

We used the imagery modes suggested above to analyze naive student's representations in the learning experiment, described as follows.

THE LEARNING EXPERIMENT

Goal

The goal of the learning experiment is to gain an insight into the mental processes, which naive students experience while constructing spontaneously (without teaching intervention) visual representations of magnetic phenomena. The explicit pictorial representations (drawings and gestures) along with the subjects' discourses reflect underlying imagery processes. This study targets the following questions:
What are the:

(1) modes of pictorial representations of magnetic phenomena, constructed by naive students
(2) relations between the pictorial representations and the physics context
(3) developmental patterns of the pictorial representations throughout the learning activity

Procedure

Sixteen ninth grades in Israel, ten girls and six boys, explored magnetic phenomena in the physics laboratory. The students had basic background in mechanic heat and electricity and no background in magnetism. They were placed into eight pairs, according to their achievements in science and math. We refer to the responses of each of these pairs as a case study (eight case studies). The learning experiment took place in three sessions, two hour each, after school hours. Each couple solved, collaboratively, a series of predict-observe-explain (POE) problems, using instructions notes and equipment such as magnets, compasses iron filling and nails. The students were asked to draw and describe verbally magnetic phenomena. They were encouraged to talk freely without worrying about the correctness of their answers.

The learning activities

Subjects were engaged in ten POE activities. In the 'predict' stage subjects were asked to draw an anticipative model (*'What will happened if...'*) In the 'observe' stage they were asked to draw a descriptive model (*'describe what happened when…'*) and in the 'explain' stage they were asked to draw an explanatory model (*Explain according to your understanding the phenomena*). The learning activity included three sessions that differed by the physics context. Physics context is defined as content of the activity and level of abstraction. The content includes the concepts involved in the task and the information provided. The level of abstraction is defined as one of the following three: concrete, microscopic or formal situations. During the first session subjects referred to concrete objects such as magnets, steel nails, compass and iron filling. For example, subjects were asked to respond to the following problem:

> “How can we distinguish between two steel bars that look identical, but one is magnetized and the other is not?”

The second session focused on microscopic situations. For example, subjects were asked to respond to the following problem:

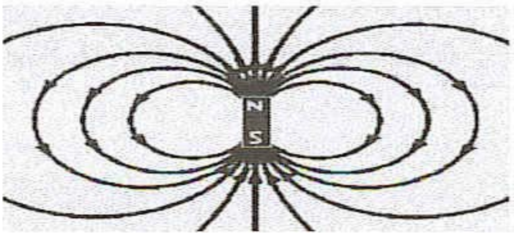
> If we break a magnet, each of the pieces will still have two poles. Suggest a structure that will explain this phenomenon

After suggesting a predictive model, the subjects were introduced to a ‘domains model’. A domain is a small naturally magnetized area. Magnetic materials contain large number of such domains, usually arranged randomly. When magnetized, all domains in the material point to one direction, leaving free domains at each end that form the poles of the magnet (Johnston 2001).

During the third session students learnt by manipulating formal representations, mainly constructing field lines. They explored iron-filling patterns to observe the shape of the field lines.

Rules for drawing field lines

1. *Magnetic field lines are directed from the north to the south*
2. *The denser the field line are, the stronger the magnetic field is*



Magnetic dipole

Figure 5*: formal rule for drawing field lines*

Data collection and Analysis

The main research tool was the POE activities, described above. The subjects' physical and verbal interactions were videotaped and field notes were taken. We collected the written responses and the diagrams, including intermediate drafts. In order to validate and complete the collected data, short interviews were taken at the end of the learning activity. The interviews were based on the subjects' responses. Responses were organized according to fine grain content units, episodes ('unit of analysis'). Each episode included a diagram, a written response and a discourse protocol. Analysis was horizontal – across groups, and vertical across sessions. Two independent evaluators validated the analysis.

ANALYSIS OF REPRESENTATIONS OF MAGNETIC PHENOMENA

The results are reported in three parts. The first part describes six modes of pictorial representations. The second part presents a profile of the representations modes in each group of learning experiences: concrete, microscopic and formal. The third part describes developmental patterns throughout the learning activity.

Modes of pictorial representations of magnetic phenomena

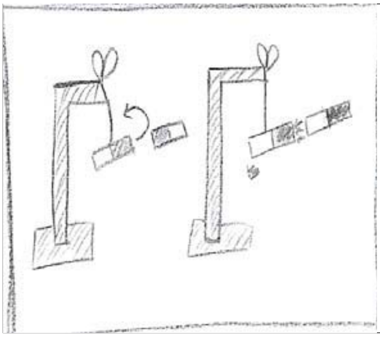
Subjects' responses were organized in 112 units of analysis. We analysed representations in two cycles of analysis: the first was based on Miller's modes of imagery, i.e. sensory-based, pure imaginary, and formalism based. The second was a process of refinement of these basic modes into six modes, described in the following section.

Sensory-based representations

We identified three modes of sensory-based representations: photographing sensory experience, projection of a former sensory experience and manipulations of sensory-based image. These modes are describes and exemplified as follows.

(a) Photographing sensory experience: This mode of representations reflects the sensory information as it is as though a photo of the situation was taken. These representations include sensory information, which is relevant to the problem (e.g. a rotation of the compass needle) as well as non-relevant features such as the magnet's colors. Subjects often use *metaphorical* symbols such as straight or circular arrows to describe direction of motion of objects in their pictures (For an overview of metaphorical symbols please see Wise 1988). The following is an example of a photographic representation of two magnets, which are place next to each other, overlaid with straight and rotational arrows.

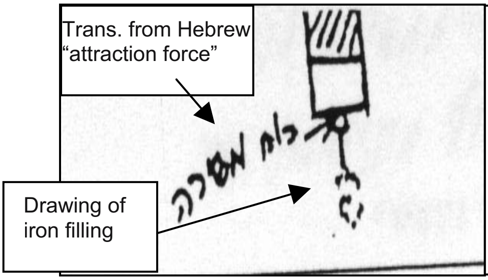
Both the diagram and words used by the subject, in figure 6 reflect a mere description of the situation of surface features such as the magnets' shape, relative position and colors. The diagram includes non-relevant elements such as the pedestal or the tie.



S.1.1: “If you attach red to blue the magnets stick to each other… and if you attach red to red the magnet turns around”

Figure 6*: Photographing sensory experience- interaction between magnets*

(b) Projection of former sensory experiences into a new sensory situation. This mode reflects former sensory experience. These representations include a reflection of sensory information, which was not in front of the subjects. In some cases the subject represented a physical situation, experience in an earlier activity (e.g. imagining a nail attracted to a magnet while predicting the direction of rotation of a compass needle) and in other cases they represented sensory situation, which was perceived outside the learning setup (e.g. imagining a powder sticking to glue, while explaining the iron filling pattern around a magnet). The following example exemplified a projection of glue properties in order to explain magnetic attraction. The subjects interpreted the magnetic force as local phenomena: “here is the attraction force”. This miss-interpretation is caused by projection of properties (of glue), which are not relevant to the problem.



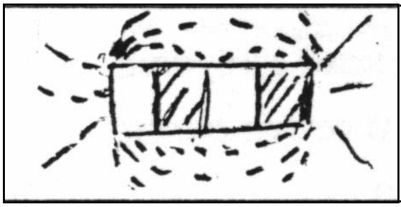
Trans. from Hebrew “attraction force”

Drawing of iron filling

S.7.1: “The nail glues to the magnet at this point … this is the point where the attraction force acts”

Figure 7*: projection of a former sensory experience (the glue metaphor)*

(c) Transformation of concrete images. This mode of representation reflects visual sensory information, like the former two modes. Yet, in this mode the sensory image in not reflected as is, but transformed, i.e. relocated, rotated or enlarged, so that it fits position of other objects described in the problem. The following example specifies iron-filling pattern around two magnets. The students 'stretched' the pattern of a single magnet to predict the configuration in a new situation.



S.6.1: "It's like a long magnet so it will be the same [as a single magnet] but ah… the 'arch' will be flat"

Figure 8*: Transformation of concrete image-" stretching" of iron-filling pattern*

Pure-imagery based representations

A considerable proportion of the subjects' representations included visual elements that obviously have never seen before as part of the 'real' physical world. The next two paragraphs describe two modes of non-sensory representations: pure products of imagination and physics-formalism-based**.**

Understanding magnetic phenomena involves construction of mental models of microscopic structures. Visual representations of microscopic structures are not visible, hence are pure-imaginary constructions. We found two sources for such representations: a projection of former sensory (macroscopic) experience into the microscopic world and manipulation of microscopic representations. These modes are describes and exemplified as follows.

(d) Projection of a former sensory experience into pure –imaginary situation. In the following example (diagram 9) the subject predicted a microscopic structure of magnetic substance, by imposing the two pole macroscopic visible structure of a magnet on the microscopic envisioned structure. The diagram shows un-magnetized object (the right diagram) in which imaginary 'N' and 'S' particles are mixed together and magnetized object in which the particles' arrangement was a projection of the magnet's colors.

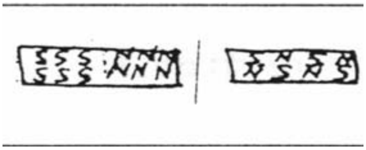
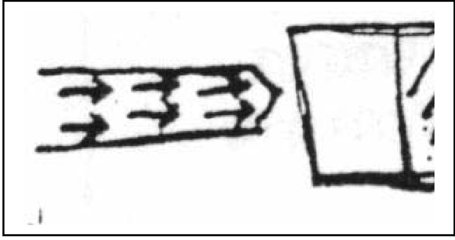


Figure 9*: Projection of a former sensory experience into pure-imaginary situation*

(e) Transformation of microscopic representations.Microscopic representations were previously learnt in mechanics and electricity classes. These representations are transformed, i.e. rotated, stretched or relocated, in order to match the mental image to the drawing presented in the problem. In the following example, subjects were presented with the scientific visual model of magnetic substance and immediately asked to design a compass. The diagram and the discourse reflect a mental rotation of the arrows, which represent pure imaginary entities: microscopic-magnetized domains.



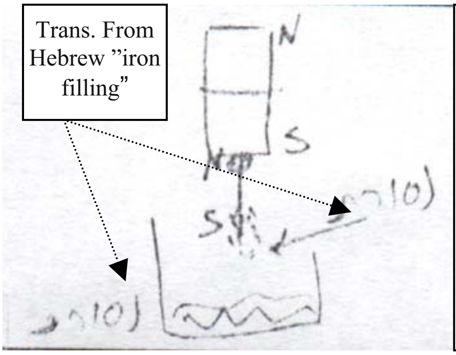
S.5.1. *"If we want the nail's tip to become the north pole we have to arrange all the arrows in the direction of the tip”*

Figure 10*: Transformation of microscopic representation*

Formalism-based representations

We found that the subjects constructed representations, based on verbal rules such as “field lines are directed from the north to the south” or “North pole attracts south pole”. This was especially used as a rule for drawing field lines. Thus this category deals integrating formalism in representations.

f) Derivation of representations from formal rules. This mode of representation includes formal symbols such as: plus and minus, ‘N’ and ‘S’. The subjects’ justified the representations they constructed by relating to formal roles. (e.g. roles for drawing field lines). In the following example the subjects identified the magnetic poles of a steal nail by using the role “North pole attracts south Pole”



S.6.2: “North and south attract each other. So…this (the head of the nail G.B) should be north and the tip south and the filling ah…north again?

Figure 11*: Derivation of representations from formal rules*

Representation of magnetic phenomena of the integration of several modes

We found that a pictorial and verbal representation may be associated with more than one mode. Many of the representations reflected sensory information, overlapped by pure imagery entities or formal symbols. For example in figure 10 we can see the shape of the nail, in addition to representation of microscopic entities. In the following example (figure 12) the diagram includes field lines that may be considered as a formal representation, while the discussion reflects two competing mental models of magnetic interaction: concrete (direction of iron filling lines) and formal reasoning based on physics conventions concerning the direction of field lines.

S3.1: "there is repulsion so the 'arch' should go outside"

S.3.2 "No, field lines go from north to south"

.3.1 "it doesn't make sense there is repulsion, so the force must go outside"

S.3.2 "There is no iron filling in the middle because of the repulsion, but field lines go from north to south. It's the rule"

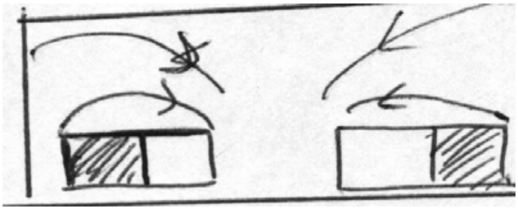


Figure 12*: integration of two modes of representations: sensory and formalism based*

Pictorial representations and context of activity: concrete, microscopic and formal

As mentioned before, the learning sessions differed by progressing level of abstraction – the first was concrete; the second was microscopic, and the third was formal. This section presents profiles of the representations that are typical to each levels of abstraction. We examined the percentage of episodes that included each mode of pictorial representation. Since episodes, often, included more then a single mode of representation, the sum exceeds 100%. Out of the 38 episodes identified during the learning in a concrete context, 70% included sensory-based pictorial representations. Results are described in table 2. The distribution of modes of representation, during the first learning session, while interacting with concrete situations, is described in table 2.

Table 2*: Frequency of modes of pictorial representation according to episodes*
Session 1:concrete phenomena

Modes of representations		**Frequency [percentage of episodes that included each mode]**
Sensory based representations	Photographing sensory experience	70
	Projection of a former sensory experience into a new sensory situation	33
	Transformation of concrete images	28
Pure imagery representations	Projection of a former sensory experience into pure–imaginary situation	10
	Transformation of microscopic representations	5
Formalism based representations	Derivation of representations from formal rules	25

The frequency of the sensory-based representations is the highest. It may be related to the concrete nature of the activity. Most episodes included photographic representations of the situation (70%). This might imply that the subjects did not yet develop a deep structure conceptual model of the physical situation. Some of the concrete representations were overlaid by microscopic and formal symbols such as arrows, + (plus), - (minus), N for north pole, S for south pole. About a quarter of the episodes included applications of the rule that “north pole attracts south pole”. The frequency of the microscopic representations is relatively low, since this session was related to macroscopic phenomena. Yet some of the subjects represented, spontaneously, microscopic processes. For example, three groups interpreted magnetization of a nail as “transfer of electrons form the magnet to the nail”. This interpretation might be related to former leaning in electricity.

Table 3 specifies the frequencies of each mode in the second learning session, which relates to microscopic magnetic phenomena. The frequency of the pure imaginary mode is the highest. Yet, about three quarters of the episodes reflected projection of a former sensory experience. This implies that subjects’ integrated photographic representations with pure imaginary mental models of magnetic substance. 47% of the episodes included transformed microscopic representations. This implies that once a microscopic representation is constructed, it may be transformed (relocated, rotated or enlarged), to fit the situation in the learning activity. Although this session was related to microscopic phenomena a major part of the episodes (about 40%) included sensory-based representations. The concrete equipments (magnets, nails) serve as boundaries in which the microscopic processes were represented.

Table 3*: Frequency of modes of pictorial representation according to episodes Session 2:microscopic phenomena*

Modes of representations		**Frequency [percentage of episodes that included each mode]**
Sensory based representations	Photographing sensory experience	31
	Projection of a former sensory experience into a new sensory situation	4
	Transformation of concrete images	13
Pure imagery representations	Projection of a former sensory experience into pure–imaginary situation	75
	Transformation of microscopic representations	47
Formalism based representations	Derivation of representations from formal rules	6

The following table (table 4) specifies the frequencies of each mode in the third learning session, which relates to construction of magnetic field-lines.

Table 4*: The frequency of each representation in percents Session 3: construction of field lines*

Modes of representations		**Frequency [percentage of episodes that included each mode]**
Sensory based representations	Photographing sensory experience	22
	Projection of a former sensory experience into a new sensory situation	28
	Transformation of concrete images	28
Pure imagery representations	Projection of a former sensory experience into pure–imaginary situation	11
	Transformation of microscopic representations	24
Formalism based representations	Derivation of representations from formal rules	77

The frequency of the formalism-based representations was the highest (77%), so was the sensory-based distribution. Subjects overlaid the formal symbols and rules on top of the concrete pattern. The frequency of pure imaginary, microscopic, representations is relatively high (35%) although the task could be performed without microscopic representations.

To summarize, these results show that modes of representation are interrelated with the physics context. Modes of representation profoundly change with the context. The frequency of the sensory based mode is the highest in the concrete session (70%), frequency of pure imaginary representations is the highest in the microscopic session, and the frequency of the formalism-based mode is the highest in the formal session. This implies that learning environment has an impact on types of representations used for learning.

Changes in modes of representations across sessions

The graph in figure 13 is a summary of the frequencies of the modes of representations across sessions. Fig. 13 shows representations vary with context and progress in the learning process. The more one learns, the more formal representations are generated. The usage of photograph-like representations decreases with time while the usage of microscopic and formal representations rises. The variety of the modes of representations increases with time. While in the first session most of the representations are sensory-based, in the third session the representations are a combination of sensory-based, formal symbols and imaginary mental models.

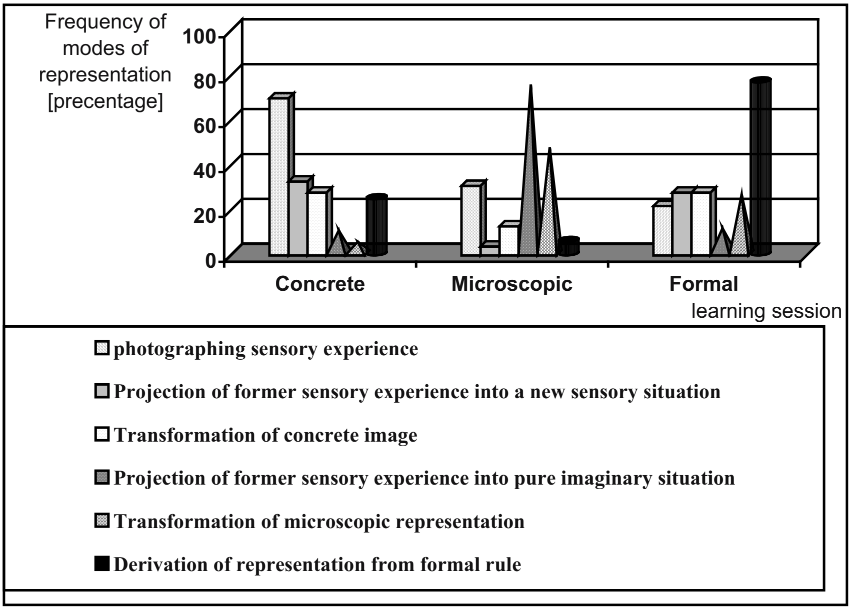


Figure 13: *Frequencies of the modes of representations in three learning sessions*

THE ROLE OF PICTORIAL REPRESENTATIONS IN PHYSICS LEARNING

This paper examined the role of pictorial representations in physics learning in the laboratory on magnetism, in three types of contexts: concrete, microscopic and formal. Results show that naive student use imagery in physics reasoning. These images are externally evident through the generation of pictorial representations. There is a partial overlap between modes of students' imagery in physics and scientific imagery in historical case studies in physics.

Students naive imagery in physics reasoning can be classified into six modes: Photographical sensory experience; Projection of former sensory experience into a new sensory situation; Transformation of concrete images; Projection of former sensory experience into pure imaginary situation; Transformation of microscopic representations; Derivation of representations from formal rules. Although it is common to suppose that knowledge used by naive students is concrete while knowledge used by expert is abstract (Chi et al 1981), in this study we showed a possible pathway for students to develop both.

Students' imagery and corresponding pictorial representations evolve with time and context of interaction: The first is somewhat obvious and expected. The second is interesting. It suggests that the context of learning has an impact on the kinds of imagery used in physics reasoning. Concrete situations call for photographic representations, while formal situations call for a combination of sophisticated overlay of meaningful symbols on top of photo-like pictorial representations. Spontaneously, students developed a sense of conveying messages by using symbolic terminology and scientific conventions. Furthermore, situated mental models, that emerged in macro-hands-on situation were adapted as thinking tools and applied to microscopic relevant new situations. Hence situational imagery tools became general imagery reasoning tools.

The following diagram (figure 14) summarizes some of the results and their relation to the theoretical framework. It displays the physicists' modes of imagery vs. students' modes of imagery, and relates the two to cognitive processes (projection and transformation. It further highlights the two major mental mechanisms involved in construction of mental-visual representations: projection of former sensory experiences and transformation of mental images. These two are widely reported in the cognitive science literature. Projections of former experience into interpretation of a new situation are studied both in cognitive science and in the physics education research community. New experiences are often interpreted by using mental schemas, constructed due to former experience. In particular sensory interaction has essential role in interpretation of physical situation (Smith DiSessa and Rochelle 1993; Johnson 1987). Johnson (1987) suggests that mental reflections of bodily experience and object manipulation have an impact on interpretation of new experiences. The tendency to project former experience into new situations might explain alternative conception of scientific phenomena (Smith DiSessa and Rochelle 1993). Projection of former experience may lead to models that do not match the conventional science. For instance, in this study, students constructed a mental model of gluing to explain magnetic attraction, and magnetic attraction as electric polarization. These models were also reported in earlier educational research.(Borges and Gilbert 1998; Driver et al 1994). Transformation of mental images is widely studied by Sheppard and by Kosslyn: mental images might be scanned, enlarged (Kosslyn 1994) or rotated (Shepard 1988). This transformation enables to fit the representation to the specific feature of the problem.

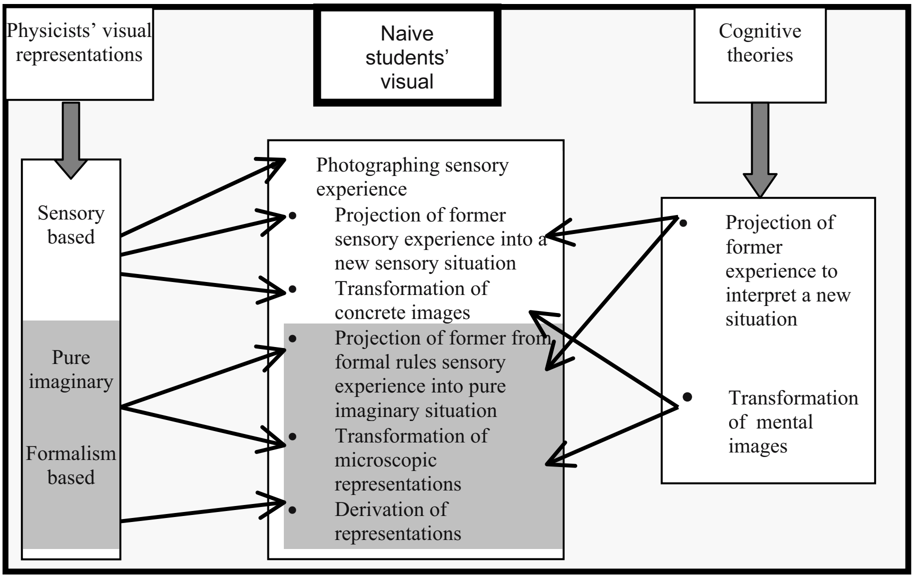


Figure 14*: Framework for interpretation of naive students' representations*

Implication for physics learning

The finding of this study, though restricted to eight case studies, suggest implications for physics learning in general.

Integrating a variety of visual representations in physics learning can facilitate qualitative understanding of physical phenomena (Reiner & Gilbert 2000, Clement & Monagham 1999; Reiner 1997; Clement 1994). In particular, we claim that a gradual progress from concrete representation into microscopic and formal representations might elaborate students' visualizations strategies. Development from concrete to microscopic and formal representations is compatible with the historical progress of visualization strategies in physics, described by Miller (2000). Using predict-observe-explain problems in phenomenological context can provide students with the opportunity to elaborate their personal mental model into accepted scientific models. It is expected that students' primary predictions will reflect pre-conception which might contradict the scientific models. These preconceptions are common and very persistent (diSessa & Sherin 1998; Smith et al 1993; Gilbert & Zylbersztajn 1985). An appropriate design of the observed situation can provide the student's with sensory information that will support conceptual change.

Collaborative construction of visual representation encourages meaningful discussion over physical phenomena (Clement & Monagham1999; Reiner 1997). Students can share sensory information to construct common representations. These representations serve as a 'window' into student's ideas and might provide teachers with communication and evaluation tool.

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