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History of Physics and Conceptual Constructions: The Case of Magnetism

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Abstract: This study documents the mental representations of magnetism constructed by students aged 15-17 and attempts to investigate whether these display the characteristics of models with an inner cohesiveness and constancy; whether they share common features with typical historical models of the Sciences; and whether they evolve through conventional teaching. Using the part of the history of physics that refers to magnetism and the research data available, we put together a questionnaire and carried out structured interviews with a total of 40 students from the 10th and 11th grades. The results showed that a small number of students is able to express reasoning within the framework of a structured model by which to approach magnetic phenomena and that this reasoning changes according to the teaching received. We also observed similarities between some of the students' representations and those of scientists from the past, though not of a wide range.

Key words: Magnetism, students' mental representations, history of physics

Introduction

The development of learning theories offers strong theoretical support for the use of the History and Philosophy of the Sciences (HPS) in the teaching of the Natural Sciences (NS). New theoretical currents in learning with regard to the Natural Sciences underscore both the importance of students' experiential mental representations and the nature of epistemological obstacles in their thinking. Both these components have fueled enquiries into the relevant character of the shapes we use in teaching the NS. Thus, among other possibilities explored in order to support this teaching, we also turned to the evolution of scientific ideas, that is to say, the history of the NS.

Today the teaching of the NS uses the History of the NS in two ways. First, by drawing on situations/research tools, which help in examining students' mental representations and the way they change. This process is selected in the hope of establishing analogies between the historical scientific models and children's representations. Given this hope, the study of the historical evolution of Natural Sciences concepts sheds light on the difficulties of human thought, since we often find similarities between the models of scientists from the past and students' mental representations, a fact which facilitates our comprehension and handling of students' difficulties (Matthews 1992; Seroglou & Koumaras, 2001; Dedes, 2005; Kampourakis & Zogza, 2007; Koliopoulos, Dossis & Stamoulis, 2007). Second, through the construction of teaching tools, since they appear to help students transcend their mental representations; to help them understand the "relativity" of scientific knowledge, and arouse their interest in the "creation" of science. (Leite 2002; Clough 2011; Paraskevopoulou & Koliopoulos 2011).

A significant amount of research has been carried out in the first area, recording students' representations and comparing them to the models introduced by scientists of the past in various sciences. For example, in Physics, there are concepts of mechanics (Halloun & Hestenes, 1985; Sequeira & Leite, 1991), action at a distance (Bar & Zinn, 1998), and electromagnetism (Seroglou, Koumaras & Tselfes, 1998); in Chemistry we have concepts of gases (Mas et al., 1987), and chemical balance (Van Driel, De Vos & Verloop, 1998); and in Biology there is the concept of photosynthesis (Wandersee, 1986). In the research mentioned above and in other similar studies, one observes, to a lesser or greater degree, a remarkable resemblance between students' representations and the models developed by scientists of the past, a fact which justifies the use of the history of the Natural Sciences as a tool for research and methodology. It is with this prospect in mind that we present this study.

In the research presented here, we have studied the relationship between the representations of 15- to 17-year-old students and the basic features of the models proposed historically in order to approach magnetism. This choice was made because of the dearth of relative studies, as shown in the pertinent bibliography; but also because we have been working systematically over the past few years on the study of children's representations of fundamental magnetic properties (Ravanis, Pantidos & Vitoratos, 2009, 2010).

The historical evolution of interpretive schemata for magnetism and electromagnetism

From antiquity to the 16th century, electrical and magnetic phenomena were viewed as a single category and in some cases magnetism was linked to gravity. Vitalistic and animistic reasoning was often applied, attributing consciousness to animate or inanimate matter (Crombie, 1959). Magnetism's prevalent schemata were two:

The first explained magnetic power through the existence of a hidden force which either was inherent in iron and was activated by the presence of the magnet, or was transferred from the magnet to iron (Thales, Plato, Aristotle, Averroes) (Crombie, 1959). Indeed, because this interpretive schema was supported by Aristotle (Guisasola, Almudi & Furio, 2005), it became prevalent during antiquity and the Middle Ages because of Aristotle's powerful influence. The second interpretive schema held that magnetic power was caused by some kind of "flow" (a "particle flow" according to the proponents of Atomism), which radiated from only the magnet or only iron (Diogenes, Empedocles, Democritus, Epicurus, and Lucretius) (Bar & Zinn, 1998).

According to the notion of physiocracy, which emerged during the Renaissance and was very influential in the early 17th century, nature pulsates with life and often appears to have its own consciousness. Magnetism was viewed as an inherent quality of bodies, but was also linked to gravity (Gilbert, Van Helmont, Kircher, Kepler). It was then that William Gilbert first proposed the separation of electrical and magnetic phenomena (Butterfield, 1949; Rossi, 1997; Westfall, 1977). Towards the end of 17th century, physiocracy was replaced by "mechanocracy", which compared the world to a machine consisting of inert bodies and moving out of a natural necessity, independent of the intelligent beings (Westfall, 1997). Its main proponent was

Descartes, who offered an innovative explanation of magnetism in accordance with his theory of spiral effluvia, thus disconnecting magnetism from gravity (Crombie, 1959; Rossi, 1997).

In the 18th century, Aepinus put forward the idea of the "magnetic fluid". According to this model, magnetic poles are areas with a surplus or a deficit of magnetic fluid. Here, the permanency of magnetization is attributed to the fixed connection of this fluid to the magnet's "ducts". Moreover, the particles of the magnetic fluid repel each other while attracting the iron particles (Home, 1976; Whittaker, 1987). Brugmans and Wilcke hypothesized the existence of two kinds of magnetic fluids which they named north and south, while Coulomb theorized that, unlike electrical fluids, magnetic ones cannot be separated since the two magnetic poles cannot be isolated (Whittaker, 1987).

Oersted's experiment which showed the magnetic results of electric current, Ampere's hypothesis according to which magnets are created by thin, cyclic, molecular currents, and proof of the relation between electricity and magnetism by Faraday, who created electric current out of moving magnets, all led in the 19th century to the founding of electromagnetism. In his attempt to mathematicize the dynamic lines which Faraday believed existed in space, Maxwell ended up formulating his field theory (Guisasola et al., 2005).

Students' representations

Research regarding magnets and magnetism conducted by Barrow (1987) on elementary school children of various ages showed that, before being taught, most students gave no explanation of magnetism. After being taught, there were references to a kind of gravity, to energy, and to electrons and protons. Less than 10% of the sample seems to have grasped the concept of magnetic poles, despite the fact that about 25% replied correctly when asked about the attraction and repulsion of the poles. Nevertheless, students tended to think that the poles only existed at the far ends of magnets.

A study by Erickson (1994) in Canada involving 9- to 14-year-old students discerned three models for the comprehension of magnetism among students. The first one, which occurs among younger students, was named the "pulling magnet", has to do chiefly with the effect of the magnet on other bodies, and does not include a mechanism or a cause given for this effect. The second one, the "emanating model", explains magnetic action in terms of rays or the emission of energy from the magnet to the bodies being attracted. Finally, the "enclosing model", is marked by the fact that the rays that emanate from the magnet are diffused around it, thus creating an area of influence. This is often referred to as the magnetic field. All three models refer to magnetic interactions and offer no information on the nature of magnetism.

Borges and Gilbert (1998) studied the representations of 15- to 18-year old students, technical students and teachers regarding electric current, magnetism and the relationship between the two. The first category, "magnetism as pulling", includes only the description of the magnet's effects, but no reference is made to the mechanism that causes this behavior. According to the second category, "magnetism as a cloud", there is a "sphere of influence" around the magnet which is responsible for the actions of the bodies that enter it. This mental representation seems to stem from the identification of magnetic action and gravitational action, according to which magnetic phenomena are interpreted as an inherent property of the magnet. The third category, "magnetism as electricity", focuses on the role played by the magnet's poles. The magnetic poles are areas, usually at the magnet's far ends, which display a surplus or a deficit of positive or negative electric charge, while magnetism itself appears as the attraction between opposing electrical charges. In the fourth category, "magnetism as electrical polarization", magnetic phenomena are explained by hypothesizing that electric dipoles exist within the magnet in such as a way so as the positive charge of one dipole to be neutralized by the negative charge of its neighboring dipole. This results in only a positive and only a negative charge at the two ends of the magnet. Indeed, for certain students, the schema is extended to include the creation of electric dipoles in a piece of iron when it is placed inside a magnetic field. This schema resembles the model described by Coulomb, who believed that a magnet is formed by magnetic molecular dipoles. In the fifth category, the direct relationship between the magnet and the object is replaced by a field-like relationship. The salient feature here is that magnetism is acknowledged on a microscopic level, as a property of all materials, even though they may have a different macroscopic behavior. This is the kind of model described by modern-day scientific textbooks. Those who have appropriated this type of model can give precise explanations of magnetic phenomena, using either the concept of elementary magnets or the concept of cyclic microcurrents.

In a study carried out by Seroglou et al. (1998) involving 10- to 15-year-old pupils and students of university education departments, and investigating whether their representations showed the existence of a relationship between electrostatic and magnetic phenomena, about half the university students and the majority of the pupils associated electrostatic attraction with magnetic attraction. Their explanations showed that they made this association because of the pull they observed in both phenomena, a fact which refers us back to the integration of electrostatic and magnetic phenomena in the history of physics from the time of Thales to the 16th century. A certain percentage of the pupils also associated these two phenomena to gravitational pull.

In their research of 9- to 18-year-old pupils' representations of action at a distance in terms of magnetism, Bar, Zinn and Rubin (1997) found that many pupils believed that air had to be present as a means for the transportation of the magnetic force. Among the 9-year-old pupils, this belief was shared by 80%, evening out at 35% in the case of the older pupils. The researchers also observed different representations in terms of the transfer of magnetic force, such as a particle flow from the magnet to an iron body.

Bradamante and Viennot (2007) conducted research on 9- to 11-year-old pupils involving the mapping of gravitational and magnetic fields and discovered that the pupils could easily grasp the concept of "abstract" magnetic lines, mainly because they can be linked to visual phenomena such as iron filings forming a pattern around a magnet. Thus, they were able to understand the properties of space around the source of the field. The pupils had difficulty in determining the orientation of magnetic needles because of their dipolic nature, but faced no such difficulties when presented with subtopics concerning the gravitational field.

Research made by Ravanis et al. (2009, 2010) studied 14- to 15-year-old pupils' representations of the magnetic field through directed individual interviews which were carried out after the teaching of magnetism and electromagnetism in the classroom. The pupils were presented with consecutive tasks and, based on the results, it appears that seven to nine out of ten pupils face significant difficulties in negotiating the features and properties of the magnetic field when they are asked to assess actual or hypothetical experimental situations.

In the study presented here, by studying 15- to 17-year old students' representations of elemental magnetism, we attempt to explore the relationship between the students' thought processes and interpretive models which were put forward in past centuries in terms of the interpretation of magnetism and the way in which these historical models can evolve into a conventional teaching method.

Research methodology

Research sample

A total of 40 students took part in the study (21 girls and 19 boys). Of these, 20 attended 10th grade (aged 15-16) and 20 attended 11th grade (aged 16-17). The students of the 10th grade had been taught the introduction to magnetism in the 9th grade (magnets, magnetic poles, the magnetic field, observing magnetic attraction and repulsion between magnets, a magnet's pull on iron filings). Also in the 9th grade the relationship between magnetism and electricity had been discussed, though not in depth, and static electricity had been taught in detail. In the time the study took place, these students had not been taught magnetism since it is not included in the 10th grade curriculum. The 11th graders had recently been taught magnetism and electromagnetism. In particular, they had been taught the concepts of the magnetic fields of magnets and live conductors, electromagnetic force and electromagnetic induction. They had been taught that the cause of magnetic properties is elemental magnets, the existence of which is due to the revolution of the electron around the nucleus as well as to the revolution of the nucleus and the electron around their own axes. Moreover, they had studied, in a lab, the effect of a live conductor on a magnetic needle and the effect of a magnetic field on a live conductor. In this case too, this had been preceded by the teaching of static electricity and electric current.

Research design

The study was carried out using structured interviews. The questions were designed based on historical models of magnetism and the earlier research concerning students' representations. From these models we have excluded the ones that link magnetism to gravity, since these are not addressed in the context of the Greek curriculum.

The research questions

The study of students' representations of the cause of magnetic properties, the concept of the magnetic field and the relationship between magnetism and electricity aimed at answering the following questions:

1. Since the various interview questions incorporated the students' representations, did the models which were used display an inner cohesiveness and consistency?

2. Do any analogies exist between the students' representations and the corresponding representations formulated by scientists of the past?
3. Are there any differences between the representations of 10th and 11th graders?

The interview

We first presented the students with two rod-shaped magnets, steel needles, a silver ring, a wooden and a plastic object, a magnetic compass and string with which to suspend one of the two magnets. The students were encouraged to examine all these objects. We then asked them questions 1, 2 and 3 (Appendix), thus creating a context for discussion within which we attempted to record the students' representations of magnetic properties.

Next, questions 4 and 5 aimed at eliciting the students' representations of magnets on a microscopic level and particularly in terms of their structure and its relation to magnetic properties. Based on the anticipated answers, we drew three alternative paths of questioning, allowing for corrections, additions, and even the transition from one path to another, depending on the answers we would receive. We posed questions 4 and 5 to all students, and then, according to the central nucleus of their answers, we proceeded as follows:

(a) If the pupil attributed the cause of magnetic properties to some sort of "substance" or to the kind of molecules that made up the magnet, we proceeded to question series 5.1a to 5.1e, in an effort to precisely define the relative representation. Since no spontaneous reference was made in these cases to a relation between electric and magnetic phenomena, we would end up at question 5.f in order to explore a possible association between the electric and magnetic character of the way in which matter behaves.

(b) If, when answering question 5, the pupil referred to electric charges, electric current or "electricity" in general as a cause of magnetic properties, we would proceed to question series 5.2. Specifically, if the pupil mentioned electric charges, we would go to questions 5.2.1a to 5.2.1c; if the pupil mentioned electric currents, we would go to questions 5.2.2a to 5.2.2c; and if the pupil mentioned "electricity" in general, we would go to questions 5.2.3a and 5.2.3b. Depending on the answer given to question 5.2.3b, we would either go on to question series 5.2.1 (concerning electric charges) or question series 5.2.2 (concerning electric currents). In all three cases we would then proceed with questions 5.2d to 5.2f.

(c) If, when asked question 5, a pupil gave another explanation as to the cause of magnetism or was unable to give an explanation, we would proceed to questions 5.3a and 5.3b, in an attempt to discover his/her precise representation of magnetism, provided it could be formulated. We would also examine whether the pupil believed there was a relation between magnetism and electricity and, if so, of what kind. (Depending on the answer, we could proceed to question series 5.1 or 5.2.) The flow chart in Figure 1 shows the paths of the fifth question:

Through the next set of questions (6-10), we tried to elicit the students' representations which are related to approaching magnetism on a macroscopic level. Question 6, which refers to the magnetic compass, creates a context for discussion which allows the students' representations to emerge and us to delve in some of their aspects.

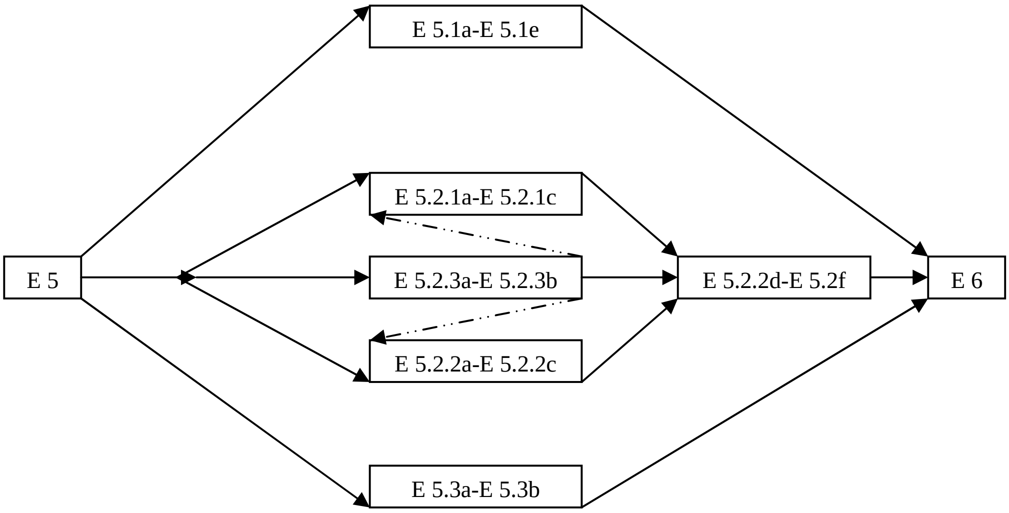

Figure 1. The paths of the fifth question

Question 7 was used to elicit possible representations related to a certain kind of "emission" on the part of the magnet towards the bodies, as had been seen in some of the historical models as well as in earlier research.

Questions 8 and 9 addressed the students' representation of the magnetic field, asking about the concept of the magnetic field itself, as well as about the properties that are attributed to it.

Question 10 had to do with the possible link between magnetic and other phenomena. The answers to these questions, together with the answers to questions 5.1f and 5.3b helped us to discover whether the students associate magnetism and electricity as general categories of phenomena. As regards the students who answered question series 5.2, i.e., the students who view electric charges as causing magnetic phenomena, this association is a given.

Research results

Next, we will present the results of the study. The students' answers to all the questions of the interview have been classified and divided into three levels based on: (1) the representations of the appearance of magnetic properties, (2) the representations of the magnetic field itself, and (3) the representations of the relationship between magnetism and electricity. At all three levels, we attempt to link the categories of the students' representations to the models that have emerged historically and to identify the possible differences between grades 10 and 11. We will also give relative examples from the students' interviews.

Representations of the appearance of magnetic properties

During the interviews, we identified six categories of representations of the appearance of magnetic properties (Table 1). The classification of the categories was carried out according to the students' answer patterns, starting from the most elaborate on a microscopic level to the most simplistic macroscopic descriptions. Let us see, then, what the students considered to be the causes of the appearance of magnetic properties.

a. *The movement of electrons.* In these representations, the students sometimes describe the orientated movement of free electrons or the revolving movement of atomic electrons, while at other times they do not define the type of electrons or movement. However, in this answer category, the appearance of magnetic properties is linked to electron movement. For example:

Researcher: What is it that causes magnetic properties?
Student 34: Electron movement in the magnet.
R: And how do you imagine this movement? How would you draw it?
S34: All of them going in the same direction. Let's say towards the left.
R: Wait, are you talking about the electrons of atoms or other electrons?
S34: I'm talking about free electrons.
R: And so how are these electrons moving?
S34: In a single direction, along a straight trajectory.
R: Is there a difference between the two poles?
S34: Yes, the electrons are going the other way.
R: So then these electrons are moving in one direction and the others in another?
S34: …no, I think they're all moving in the same direction.

b. *Magnetic dipoles that exist inside the magnet which are caused either by pairs of positive or negative charges, or by the distribution of the electrons in each dipole.* The following dialogue is typical:

R: What causes magnetic properties?
S30: The molecules in a magnet are all facing in one direction.
R: So how do you imagine the inside of a magnet?
S30: There are magnetic dipoles inside it.
R: What do you mean dipoles?
S30: Having two poles – a north and a south. Each molecule, that is.
R: Do you mean that each molecule is a magnet?
S30: Yes.
R: Let's look at each molecule. What might cause the fact that it is a dipole?
S30: The distribution.
R: The distribution of what?
S30: The distribution of electrons.
R: How do you mean?
S30: More electrons here, fewer electrons here.

c. *The existence of opposite charges at the magnet's poles which are either equally distributed at each pole or exist in greater numbers at the poles' extreme points.* These charges may be moving or not, but this movement, provided it exists, does not affect the magnetic properties, as is made clear in the following example:

R: What causes magnetic properties?
S38: They are caused by the fact that the electrons gather at one of the magnet's poles and so the other pole becomes positively charged.
R: So, if we made a magnet, draw me what you think it would look like.
P38: At one end we'd have positive charges and at the other end negative charges – the north and the south pole.

R: You're not drawing anything here towards the center. Aren't there any charges here?
S38: They've accumulated at the extreme points of the poles.
R: Are they stationary or are they moving?
S38: Um… do electrons revolve?
R: Does that affect magnetic properties?
S38: Whether electrons move or not?
R: Yes.
S38: No, it doesn't affect them.

d. *A certain "substance" that's contained in the magnet.* In terms of quantity, this "substance" appears in excess or in deficit at both poles; in terms of quality, it is of a different kind at each pole. This same category can include students' representations which attribute the magnetic properties to "molecules" of the magnet that are either laid out differently on each pole, or are sparser or denser on each pole. Indeed, reference to molecules here is not made in the sense attributed to them by the sciences, but rather as a vague allusion to the microscopic features of magnets. The same applies to the students that talk about a certain "substance". For example:

R: What do you think causes magnetic properties?
S16: Magnets contain certain substances that attract.
R: So then the magnet contains another substance from another body?
S16: Yes.
R: How do you picture it? Is it the same substance everywhere or different kinds?
S16: Different kinds.
R: Where?
S16: On the red and the white.
R: So then at each pole.
S16: Yes. Different kinds at each pole.
R: And if we cut it in half what will happen?
S16: Each piece will become separate. Each kind will be separate...

e. *The magnetic properties are caused by the "magnetic field", which is perceived as an area where forces are exerted.* No reference is made to its origin on a microscopic level, as we can see in the following example:

R: What causes magnetic properties?
S32: Um… magnets create a field, a magnetic field…
R: Yes…
S32: And forces are created which attract, let's say, iron things...
R: And how does the magnet create the field? Is there something inside it that creates the filed?
S32: No, the magnet is made of the same material.
R: It's a particular material.
S32: Yes.
R: What is it in the magnet's material that gives it its properties? Is there some kind of movement? How do you picture it?
S32: The field lines that pass through it and outside it.
R: Which are created how?
S32: I don't know.

f. *The "nature" of the magnet.* The students refer to the material or the forces exerted by the magnet without being able to give further explanations. Here is a typical example:

> R: What do you think causes magnetic properties?
> S19: You mean attracting bodies?
> R: The attraction of certain bodies, the attraction between opposing poles and the repulsion between like poles.
> S19: …
> R: How do you picture it? Is there something inside the magnet?
> S19: I don't know… I can't say.
> R: when you say that it attracts bodies, what do you picture?
> S19: Certain forces are exerted.
> R: And what causes them?
> S19: The magnet.
> R: Do you think it contains something that creates these properties?
> S19: No, it's the magnet itself… the material.
> R: The material of the magnet?
> S19: Yes.
> R: Is it the same type of material at each pole or is it different?
> S19: The same.
> R: Then why are like poles repulsed and opposite poles attracted?
> S19: I don't know.

As we see in Table 1, in the 10th grade, one pupil attributed magnetic properties to dipoles and seven thought that they were caused by the separation of electric charges at the magnet's poles. Ten out of twenty students thought that magnetic properties were caused by a "substance" contained in magnets (a single substance, two kinds of substances or the way the molecules are arranged), while two students attributed magnetic properties to the magnet's "nature". In the 11th grade there were five students who attributed magnetic properties to electron movement and one who attributed them to magnetic dipoles. Nine out of twenty students thought that magnetic properties are caused by the separation of electric charges at the magnet's poles, two thought they were caused by the magnetic field, and two attributed them to the magnet's "nature".

Table 1. Representations of the appearance of magnetic properties

Representation	Grade 10		Grade 11	
	Subjects	f	Subjects	f
Electron movement			22,25,28,34,37	5
"Magnetic dipoles"	6	1	30	1
Opposite charges/poles	1,3,5,9,12,14,15	7	23,24,27,29,31,33,36,38,40	9
Substance – "molecules"	2,4,7,8,10,11,13,16,18,20	10		
Magnetic field			21,32	2
Nature of magnets	17,19	2	26,35,39	3

Representations of the magnetic field

In almost all of the students' answers, the magnetic field is acknowledged as the space within which magnetic forces are exerted. However, the way in which the magnetic field takes shape in their mind leads to three different representation categories, ranging from the ones in which the magnetic field is acknowledged as a wider area around a magnet in which forces are exerted to those which closely link the magnetic field to the characteristics of the magnet that creates it: the magnet's shape, field lines, and the magnet's poles (Table 2).

a. In the first category, the magnetic field is a finite space in which forces are exerted. The magnetic field is represented simply by the field lines which are imaginary. Only in one case did a student (S6) express the thought that the magnetic field extends over a limitless area and has no particular form. The two excerpts below are representative of this category:

> R: What do you imagine about the concept of the magnetic field? What is a magnetic field?
> S38: It is the space in which if a suitable body is placed, a force is exerted on it.
> R: What does the magnetic field around a magnet look like? Does it have limits? How would you draw it?
> S38: It has certain limits… There are the field lines and they begin from the north pole towards the south pole and they are closed.
> R: Are they real lines or not?
> S38: No, they are imaginary.
> R: Are they made of some sort of material?
> S38: No.
> R: Draw me the magnetic field around the magnet as you imagine it.
> S6: It's everywhere… the entire space.
> R: Draw it.
> S6: How can I draw it? You mean the forces?
> R: No. Does it have a shape, does it have limits?
> S6: No, it doesn't have limits; it spreads through space.
> R: Even far from the magnet?
> S6: Yes, even far from the magnet there are forces.

b. In the second category of representations, the magnetic field is in the shape of a closed circle or an ellipsis around the magnet. It does not appear to have been given a different consistency than the space that surrounds it. In terms of the force of the field, assessments range from it being considered equally powerful at all its points, to having the greatest force at its far ends and almost zero power at its center. An example:

> R: What comes to mind when someone mentions a magnetic field? What's a magnetic field?
> S8: It is the space within which bodies are attracted by a magnet.
> R: Therefore, if I have a magnet, draw me a magnetic field. How do you picture it?
> S8: I believe it'll be a circle within which bodies will be attracted.
> R: So then if I put this steel needle here or here, does it attract it?
> S8: Yes, yes.
> R: If I put it here, outside the circle?
> S8: No.
> R: Therefore the magnetic field has certain limits?
> S8: Yes.

Table 2. Representations of the magnetic field

Representation	Grade 10		Grade 11	
	Subjects	f	Subjects	f
A finite area within which forces are exerted in relation to field lines	6,9,15	3	22,23,24,25,26,27,28, 29,30,32,34,37,38,40	14
Closed ellipsoidal or cyclical area	1,2,3,4,5,7,8,10,11,13,14, 16,17,18,19,20	16	21,31,35,39	4
Closed charged area	12	1	33,36	2

c. In the third category, the magnetic field is again shaped like a closed circle or an ellipsis around the magnet, but now it contains electric charges which are either both positive and negative or only electrons, as can be seen in the next example.

R: What comes to mind when someone mentions a magnetic field?
S12: A space within which there are attractions; electromagnetic attractions.
R: How would you draw a magnetic field around a magnet?
S12: It's kind of circular and there are charges in it.
R: What kinds of charges?
S12: Positive and negative charges.

As we see in Table 2, in the 10th grade, three students form a representation of the magnetic field as an area in which forces are exerted in the broader space around the magnet or the dynamic lines. Sixteen students acknowledged the magnetic field as a cyclical or ellipsoid area, while one student saw it as a cyclical or ellipsoid area that contains charges.

In the 11th grade, the representation of the magnetic field in the case of fourteen students was the wider area defined by the dynamic lines; in the case of four students it was the cyclical or ellipsoid magnetic field; and in the case of two students it was a cyclical-ellipsoid magnetic field that contained charges.

Representations of the relationship between magnetism and electricity.

During the interviews, we often had the opportunity to observe the possible associations students make between magnetic and electrical phenomena. Accordingly, their answers were divided into 3 categories. Examples of such dialogues appear in earlier sections of this paper.

a. The first category consists of representations in which the relationship between magnetism and electricity is recognized and explained based on the scholastic scientific model, i.e., the model of orientated currents. Here is an example:

R: So then there's a connection between magnetism and electricity?
M28: Yes.
R: What causes electricity?
M28: The orientated movement of electrical charges.
R: Magnetic charges?
M28: I said… the orientated movement of electrons in magnetic areas.

b. The second category consists of representations in which the relationship between magnetism and electricity is recognized and described in microscopic or macroscopic terms, but is not explained satisfactorily.

> R: Is there some connection, some relationship between electricity and magnetism?
> S10: Um… I think there is, because in electricity, in certain experiments we did, we see that it electrifies certain… hair, for instance. Electricity electrifies it and attracts it.
> R: So then there's a similarity in that they both attract.
> S10: Yes. Different things, of course, but they both attract.
> R: Is there any other connection between them?
> S10: No.

c. In the third category, no relationship between electricity and magnetism is acknowledged, while in two cases the students were unable to reply.

> R: Is there a connection between magnetism and electricity?
> S21: No.
> R: Are there certain phenomena that resemble magnetic phenomena?
> S21: …I don't think so.

In Table 3 we see that a good understanding of the relationship between magnetism and electricity based on the orientated currents model was displayed by 5 11th graders, while 11 10th graders and 13 11th graders saw connections between magnetism and electricity but were unable to offer satisfactory explanations. Finally, 9 10th graders and 2 11th graders didn't see any connection between magnetism and electricity.

Table 3. Representations of the relationship between magnetism and electricity

Representation	Grade 10		Grade 11	
	Subjects	**f**	**Subjects**	**f**
Approaching the school model of the magnetism-electricity relationship			22,25,28,34,37	5
Acknowledging the magnetism-electricity relationship without satisfactory explanations	1,2,3,5,6,9,10,12,13,14,15	11	23,24,26,27,29,30,31,32,33,36, 38,39,40	13
Not connecting magnetism to electricity	4,7,8,11,16,17,18,19,20	9	21,35	2

Discussion

Based on the results of the documentation of the students' representations, we will try to answer the three specific research questions we posed initially.

Do the students use certain representations consistently?

By studying the results, we see that there are certain students who express thoughts within the framework of a structured model by which to approach magnetic phenomena. Thus, 5 11th graders (S. 22, 25, 28, 34 and 37) consistently associate magnetism with electricity. Of course the associations they make are not always successful, as, for example, in the question of the kind of movement electrons display in the creation of a magnetic field. But in the case of all five subjects, the systematic reference to the connection between electrical and magnetic phenomena was accompanied by a better understanding of the form of the magnetic field and a satisfactory approach to the connection between electricity and magnetism. This consistent reference based on the restrictions of the scholastic model shows that the teaching of electromagnetism in the 11th grade allows a more cohesive approach to the topics under discussion.

Moreover, we observed a consistency in the answers of the subjects that do not link magnetism and electricity in any way. Indeed, students who do not associate magnetic properties with any kind of charges (S. 4, 7, 8, 11, 16, 17, 18, 19, 20, 21, 35), go on not to recognize any link between magnetism and electricity. This approach is indicative of a specific way of thinking, in which magnetic phenomena are attributed to the particular nature of certain materials.

Are there analogies between the models proposed historically and students' representations?

In our effort to link the students' representations to the historical models proposed, we observed that the representations that acknowledge the rotational movement of electrons are similar to the models developed by Ampere and Weber, which introduced molecular cyclic currents as the cause of magnetic properties. The particular representation we investigated also distinguished between the revolution of the electron around the nucleus and around its own axis, thus approximating contemporary theory as it is presented in modern-day textbooks and obviously influenced by them.

In the second category, we observed a relative similarity between the students' representations of magnetic dipoles and Coulomb's model, which proposed the existence of permanent magnetic dipoles in a magnet, in an aim to explain the inability to separate the two magnetic poles. But there is a difference in the explanation, since, according to Coulomb's model, magnetic dipoles are created by separating the two kinds of magnetic fluids within the molecules of magnetic bodies, while according to the students, magnetic dipoles are formed by separating the electric charges in the molecules of the bodies.

We observed a remarkable similarity between the representations which referred to a certain "substance" and the scientific representations of the 18th century. In particular, the subcategory that mentions one type of substance is similar to Aepinus's model of a single magnetic fluid. In this case too, magnetic properties are caused by something "special" that exists in the magnet and appears in excess at one pole and in deficit at the other. The subcategory that mentions two types of substance resembles the model of the two magnetic fluids which lie at the magnet's two poles and are repulsed or attracted according to their type.

Table 4. Similarities between models proposed by the scientists of the past and students' representations

Historical models	Students' representations
Magnetic force	"Nature" of magnets
Magnetic fluid	Substance – "molecules"
Coulomb's model	"Magnetic dipoles"
Ampere's and Weber's model	Electron movement (rotational)
Faraday's model	Magnetic field

In the category of representations that consider the magnetic field to be the cause of magnetic properties, we observed a relative similarity with Faraday's model in terms of the way in which the magnetic field is viewed. Without referring to a field, Faraday filled space with dynamic lines that exist within the natural condition of space. These lines transfer magnetic force and are the cause of magnetic results. A similar image was located in students' mental representations in this category.

Finally, in the representations in which magnetic properties are attributed to the "nature" of the magnet, we observed a similarity with the representations which were prevalent from antiquity to the 16th century. In these representations, the "nature" of the magnet itself, though not in an animistic way, is responsible for its magnetic properties (Table 4).

We observed no similarity between the historical models and the students' prevalent representation, which recognized the separation of electric charges as being the cause of magnetic properties. It appears that students who are familiar with static electricity before learning about magnetism use their representations regarding static electricity in order to explain magnetic phenomena. This did not occur in the case of scientists in the past, since the models of static electricity appeared later in the history of science. In addition, several of the magnetism models that appear in the history of science did not appear in the students' representations. A typical example which did not appear here was the model of the particle "flow" from the magnet to other bodies, which was widely accepted in Antiquity and the Middle Ages.

Are there differences between the representations held by 10th and 11th graders?

The third question concerned the possible difference between the representations of 10th graders and 11th graders. In terms of the appearance of magnetic properties, we saw that in the 10th grade these are attributed mainly to a certain special "substance" and less to a type of electric charge. In the 11th grade, the notion of a magnetic substance is completely abandoned and the majority of the answers mentions either the existence of charges or the movement of electrons.

In regard to the magnetic field, the majority of representations in the 10th grade is linked more to a static viewing of its shape which is closely tied to the shape of the magnet. In the 11th grade, the majority of the students' answers centers on representations of dynamic lines.

The relationship between magnetism and electricity differs considerably in the representations of 10th graders compared to 11th graders. Less than half the 10th graders simply recognize, in an unsatisfactory way, a link between electric and magnetic behaviors; more than 6 in 10 11th graders recognize this relationship in the same way; and 1 in 4 approaches the scientific model as it is used in school.

The differences between 10th and 11th graders in the representations observed in all three questions can be attributed to the teaching of electromagnetism in the 11th grade. Indeed, topics such as the origin of magnetic properties, the nature and form of the magnetic field and the relationship between the magnetic and electric behaviors of matter, are all included in the models we use in teaching. However, we must note that, even though the representations of 11th graders are improved compared to those of 10th graders, they are not satisfactory in terms of the teaching model, a fact which raises questions regarding the organization of the teaching of this model.

Conclusions

In this study we have tried to document the students' mental representations of magnetism and attempted to investigate whether these display the characteristics of models with an inner cohesiveness and consistency; whether they share common features with typical historical models of the Sciences; and whether they evolve through conventional teaching. From the results it appears that a significant number of students were able to construct cohesive and consistent representations of magnetism. From among the representations documented, some have appeared in previous studies. For example, the "Opposite charges/poles" and "Magnetic dipoles" of the present study resemble the "magnetism as electricity" and "magnetism as electrical polarization" representations encountered in the research by Borges and Gilbert (1998). Especially interesting is the category of representations that attribute magnetic properties to a "substance," which we associated to the historical model of a magnetic fluid, and which we did not come across in earlier research. Moreover, certain representations that refer to a certain "emission" on the part of the magnet, such as the "emanating model" and the "enclosing model," which occur in Erickson's research (1994) do not occur here.

In the subjects we studied here, despite any similarities between the representations held by the students and the characteristic historical models of the Sciences, we cannot claim to have observed analogies on a wide scale. The representations held by scientists of the past were parts of conceptual systems, while the mental representations held by students are much less cohesive. Besides, the relative scientific models were developed within a different cultural framework. Moreover, scientists and students have different cognitive backgrounds and approach natural phenomena from completely different perspectives. Thus, we'll agree with the point of Seroglou et al. (1998) that it appears that we cannot draw parallels between students' representations and historical models, not even regarding fundamental magnetism. All we can do is to maintain the comparison on a level of similarities. Such a comparison could produce interesting ideas concerning the problems that students might encounter in comprehending magnetic phenomena.

Indeed, our research indicates points at which the students' thought processes approach the basic elements of the models put forward historically in regard to magnetism. Therefore, based on these, we can try, through specially orientated didactic interventions, to transform the students' representations into representations which are related to those of the modern scientific models we have constructed for education (Dedes & Ravanis, 2009a, 2009b). Besides, as our research showed, conventional teaching does not seem capable of guiding students' thought processes towards the necessary reasoning.

Our study is, of course, limited by the small sample size (40 students) and their specific profile (students of one high school from a provincial city). Our research methodology using structured interviews may have affected students' answers, although every effort was made to minimize this possibility. Further studies with larger sample sizes and students of different backgrounds could benefit the research on students' representations of magnetism and could validate the conclusions of this study.

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Appendix: The questions of the interview

We supply the following objects: two rod-shaped magnets, iron filings, steel needles, a silver ring, a wooden or plastic body, a magnetic compass, and a piece of string with which to hang one of the two magnets. We give the children the objects to examine, we answer whatever questions they may have and then we immediately begin the discussion. The series of questions was as follows:

1. What does the magnet do?
2. Does it attract all these objects, or not? And if not, why is that?

3. (*We hang one of the magnets from the piece of string so that it is suspended in the air; we give the other one to the student and ask him/her to bring it close to the first magnet.)* What kind of force does one magnet exert on the other? Is the force the same everywhere, or does it depend on the position of the magnets? Why is this?
4. Why do you think the magnet acts this way?
5. Does the magnet contain something or is there something inside the magnet that gives it these properties? And what might that be?
► *If the student refers generally to a certain "substance", then a mental representation resembling the model of the magnetic fluid will emerge.*
5.1a. How do you picture this "substance"?
5.1b. Is there only one kind of fluid or more? How many? *(One or two kinds of magnetic fluid)* What forces are exerted between them?
5.1c. What will happen if we cut the magnet in pieces? How do you explain the magnet's poles in relation to its "substance"?
5.1d. How do you explain the fact that the magnet attracts certain materials but not others? How is this related to the "substance" of the magnet?
5.1e. Can you draw what you think the inside of the magnet looks like?
5.1f. Are electricity and magnetism related? How do you picture this relationship?
► *If the student uses words such as electric charges, electric currents or electricity, then we try to elicit the precise mental representation.*
• *If he/she mentions electric charges:*
5.2.1a. How do you think that electric charges create magnetic properties?
5.2.1b. How are the charges distributed within the magnet? *(Distribution at the two ends, surplus or deficit, electric dipoles)*
5.2.1c. Are they immobile or are they moving?
• *If he/she mentions electric currents*:
5.2.2a. How do you think electric currents create magnetic properties?
5.2.2b. What kind of electric currents? How are they created?
5.2.2c. How do they move within the magnet?
• *If he/she mentions electricity in general*:
5.2.3a. How do you think that electricity creates magnetic properties?
5.2.3b. Are you referring to electric charges or electric currents? *(Depending on the answer we go back to the questions above.)*
In all three sub-cases we ask the following questions:
5.2d. What will happen if we cut the magnet in pieces? How do you explain the magnet's poles in relation to its electric charges or its electric currents?
5.2e. How do you explain the fact that the magnet attracts certain materials but not others?
5.2f. Can you draw what you think the inside of the magnet looks like?
► *If the student gives another explanation (first we try to elicit the mental representation) or cannot give an explanation*:
5.3a. Can you draw what you think the inside of the magnet looks like?
5.3b. Are electricity and magnetism related? How do you picture this relationship?

6. How do you imagine a magnetic compass works? What is it that pulls the magnetic needle in that direction?
7. How do you think that magnetic forces are transferred to bodies? Is it something that the magnet emits? What could that be? How would you describe it?
8. What does the concept of the magnetic field make you think of?
9. How do you imagine the magnetic field? Does it have limits? And how far do they extend? Does it take up space instantly, or does it take time? And if so, how much time?
10. There are certain other phenomena that resemble magnetic phenomena. In what way?

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