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Finnish Secondary Students' Mental Models of Magnetism

Abstract:

We examined Finnish lower secondary students' mental models of magnetism through their drawings, written explanations and interviews. Secondary students in Finland (N=12) engaged in six lessons designed specifically to target three key concepts in understanding magnetism: structure and organization (magnetic domains), magnetic fields and magnetic interactions. We describe how, with a finite number of key concepts introduced, students reflected upon and revised their mental models of magnetism and magnetic interactions towards more sophisticated and normative scientific views. We found two new categories of students' models: the pole model and pole/field model. The critical moments in evolving the models happened during the investigations regarding understanding magnetic fields and magnetic internal structure. This article gives an example for teachers and researchers of how to follow students' development of mental models in science.

INTRODUCTION

Magnets are familiar and fascinating objects within the everyday experience of most people, and, as any teacher who has taught a lesson in magnetism knows, learners of all ages can hardly resist the temptation of playing with them. One reason that magnets may provoke such interest is that they provide a clear illustration of force acting on another object without physically touching it. Yet despite our fascination with magnets, people's conceptions of magnetism and magnetic phenomena have not been investigated as extensively as other physical phenomena (Guisasola, Almudi, & Zubimendi, 2004; Hickey & Schibeci, 1999; Ravanis, Pantidos, & Vitoratos, 2010).

Concepts of magnetism pose a challenge for learners, as these concepts require higher levels of cognition and mental imagery than more concrete and tangible concepts (Borges & Gilbert, 1998; Guisasola et al., 2004). Children also have difficulty understanding concepts that they cannot see, even after hands-on inquiries (Olson, 2008). For example, the idea of an object causing an invisible force to be exerted on another without touching or of an object being attracted equally to either pole of a magnet are counterintuitive for children. Even after long and repeated instruction, students' models of magnetism are likely to fall short of target sophistication (Borges & Gilbert, 1998; Constantinou, Raftopoulos, & Spanoudis, 2001).

Existing research into students' conceptions of magnetism has focused primarily on three topics: interactions among magnets and other objects, the association of magnetism with charge and characteristics of the magnetic field. However, little work has been done to examine the ways in which students' conceptions of magnetism are related to one another, how they change over time or how they build on one another – that is students' trajectories of learning about magnetism. This research will more systematically inform understanding of students' trajectories of learning about magnetism. Thus, this research will inform curriculum development for K–12 instruction as well as the professional development of teachers who teach magnetism in their classrooms.

We investigated students' knowledge and thinking about what magnets are, what characteristics materials have that can be affected by magnets and the consequences and mechanisms of magnets and materials interacting, all from the perspective of students' mental models. We use mental model as an individual's internal representation of a phenomenon that is the basis of reasoning, application and learning (Greca & Moreira, 2002; Johnson-Laird, 1983). In the context of instruction with a series of design-based (Wiggins & McTighe, 2006) lessons and assessments, we investigated how one class of secondary students in Finland constructed, critiqued and revised their mental models of magnetism and magnetic phenomena. Our research questions included the following:

1. What is the nature of Finnish secondary students' mental models of magnetism?
2. When and how do the content and conceptual sophistication of students' models of magnetism change during the course of instruction?

THEORETICAL FRAMEWORK

The theoretical framework of this study was derived from contemporary and time-honoured research regarding mental models and students' ideas about magnetism.

Students' Ideas about Magnetism

Haupt (1952) studied elementary school students' ideas about magnetic interactions, asking them, "Why do magnets pick up metals?" He categorized the answers into seven distinct conceptions from least accurate ("It has glue on it") to most accurate ("There is a magnet inside a metal"). Stepan (1994) listed seven representative middle and high school student non-normative conceptions about magnetism, also including magnetic fields in magnetic interactions:

1. The strength of a magnet is determined by its size.
2. Magnets attract all metals.
3. All silver-coloured objects are attracted to magnets.
4. Magnets pass through paper but not wood, notebook, table or other thick materials.
5. Magnetic fields are only created by magnets.
6. Magnetic fields are two-dimensional rather than three-dimensional patterns around a magnet.
7. Magnetic field lines exist only outside a magnet.

The sources of these misconceptions were not identified, but later studies have found that at least the two first misconceptions in the list apply already with elementary students (Burgoon, Heddle, & Duran, 2010). Documented non-normative conceptions about magnetism also include ideas that magnets are electrically charged; electrostatic and magnetic interactions are the same; and a charged object will be attracted to a magnet (Borges & Gilbert, 1998; Haupt, 1952; Maloney, 1985). Even older physics students expect a magnetic force whenever an electric charge is placed in a magnetic field, and they also have a fluid flow interpretation of the effect of the magnetic field on the moving charged particle (Maloney, O'Kuma, Hieggelke, & Van Heuvelen, 2001). Many students also may believe that the magnetic field has a finite boundary (Bar, Zinn & Rubin, 1997) or that the field lines are concrete entities (Guisasola et al., 2004; Guth & Pegg, 1994).

Cheng and Brown (2010) studied elementary students' initial explanations about magnets and found two types: intuitive and abstract. Third-grade students were capable of formulating explanatory models and tended to provide more creative explanations based on intuitive thinking than did sixth-graders, relying more on verbal or symbolic prior knowledge, which they still were not able to explain. Connecting the two types of knowledge was found to be essential to building a sophisticated normative explanatory model.

While a few non-normative ideas about magnetism have been catalogued, less attention has been given to the way in which students' mental models of magnetism evolve through learning. What is needed is an examination of the development of students' concepts of magnetism in a larger context across physical phenomena of magnetism. Examining students' construction and revision of mental models of magnetism, how those models are subject to change in light of new evidence and how they might be tested in varied applications (for example across scale) will help define pathways for learning as well as providing students opportunities to build upon and reinforce science content learned from other domains (for example size and scale, the particle nature of matter and the revisionary nature of scientific knowledge).

Mental Models

Models are scientific constructions designed to predict and explain phenomena in nature. Learning science is not simply using models posed by others and taken for granted but is also making, revising and justifying models (Lehrer, 2009). Each individual interprets models in their own way according to their experiences. Mental models are the unique mental representations constructed by an individual in interaction with the natural world and other persons (Driver, Asoko, Leach, Mortimer,

& Scott, 1994). It is through the mental model that we evaluate statements, make predictions or construct explanations regarding a phenomenon. When our evaluations and predictions agree with the scientifically accepted views, one can say the mental model is aligned with the scientific model (Greca & Moreira, 2002). Mental models provide a framework for the incorporation of new observations into existing models to make sense of what was learned (Johnson-Laird, 1983).

Eliciting students' mental models. Insight into students' mental models can be accessed by diverse techniques. For example, researchers have used written explanations to open-ended questions, think-out-loud accounts, written journal descriptions, drawings and interviews.

Specifically, drawing is an effective means of tapping into students' holistic understanding and provides a free form of expression, less likely to direct the student trying to match their knowledge with that of the teacher (Ainsworth, Prain, & Tytler, 2011; Tytler, Prain, Hubber, & Waldrip, 2013). Drawing also allows an alternative for those students who either have difficulty with expressing themselves in writing or who would prefer not to (Rennie & Jarvis, 1995). Drawing is good for illustrating concepts like magnetic fields and internal structure more easily than would be possible in writing (Dove, Everett, & Preece, 1999). We used these methods in combination to provide a means of triangulation for clarity in understanding the essential elements of students' mental models.

METHOD

We employed an interpretive research design to analyze and characterize students' mental models of magnets, magnetic phenomena and magnetic interactions.

Setting and Participants

The participants ($N = 12$; 8 male, 4 female) were ninth-grade students in a public secondary school in Finland. The students comprised a nonrandom sample. The students had received no formal secondary instruction in magnetism prior to the instruction during this research. The gender distribution of the sample was not necessarily representative of the class as a whole, but it consisted of those students whose signed consent and assent forms were returned. The ages of the students ranged between 15 and 16 years.

The school in which the study was conducted was a university-affiliated basic and upper secondary school, located in central Finland. The school offers basic and upper secondary education and supervised teaching experience as well as opportunities for research, experimental and development activities and continuing education for teachers. The students are appointed from the region closest to the school and are not selected by grades. Students in the school are accustomed to pre-service teachers, guest lecturers and researchers being present and part of their daily routine. Each of the investigations and lessons that were part of instruction for this research was co-taught by one member of a cadre of pre-service teachers along with the regular subject teacher.

Instruction

The magnetism unit that served as the context for examining students' mental models consisted of six design-based lessons that focused on a limited number of concepts. The concepts were sequenced to enable students to construct coherent knowledge about magnetism: structure and organization (magnetic domains), magnetic fields and magnetic interactions. We aimed for these concepts to be most salient in constructing a coherent understanding of magnetism and of the behaviour of magnetic materials. All instructional materials and assessment instruments (Sederberg & Bryan, 2009), originally written in English, were translated into Finnish by the first author, a native Finnish speaker who was fluent in both languages. All instruction was conducted in Finnish.

To construct a coherent understanding of scientific principles, learners must be able to formalize and reflect upon their understanding of scientific concepts as they develop them (Clement, 1989). While

we recognize that students' construction, critique and revision of their mental models was related to instruction, our goal was not to evaluate the effectiveness of the instruction but rather to document the evolution of students' mental models of magnetic phenomena in the context of regular classroom instruction.

In this sense, we focused on a few key principles of magnetism across a variety of situations, emphasizing interactions (for example between two magnets; magnet and wire; two magnetized wires; magnet and iron nail, reversing positions) and predicting how and explaining why these kinds of interactions occur. The range of learning activities and assessments we employed was as follows (Sederberg & Bryan, 2010):

1. Provide multiple opportunities for students to make their own ideas explicit.
2. Challenge students' mental models with events which might be considered discrepant.
3. Encourage students to reflect on their thinking.
4. Incorporate small-group brainstorming and whole-class discussions for sharing ideas and interpreting different mental models.
5. Allow students to apply and reinterpret their mental models in different a range of situations.

A short description of the lessons and content is shown in Table 1.

Table 1. Lessons and their content

Conceptual focus	Lessons					
	1	2	3	4	5	6
Characteristics of magnets (what magnets are, how magnets work)						
Kinds of magnetic interactions (attraction, repulsion, no interaction)						
Magnetized and non-magnetized (how a material is changed by magnetizing)						
Magnetic fields (force, cause change, consequence of being magnetized)						
Magnetic domains (structure, alignment, polarity reversible)						

Data Sources

Sources of data for this study consisted of pre- and post-tests, mental model representations in the form of written explanations and drawings from laboratory investigations, written explanations and drawings from informal embedded assessments, and semi-structured interview transcripts. Their chronological order is shown in Table 2.

Pre- and post-test. The identical pre- and post-test instruments were previously piloted in U.S. and Finnish classrooms (Sederberg & Bryan, 2009; Sederberg & Bryan, 2010; Sederberg, Latvala, Lindell, Bryan, & Viiri, 2010) and consisted of eight free-response items and one series of agree/disagree statements. An example of a test question is shown in Figure 1. The pretest was administered one week prior to instruction; the post-test was administered the day after instruction ended. A primary focus of the pre- and post-test was on magnets, their characteristics and function and the mechanisms by which magnets and magnetic materials interact, themes which were carried throughout instruction. The pre- and post-test instrument had a paper and pencil format.

Table 2. The schedule for the data collection. Students were interviewed immediately after the pre-test, post-test and Lesson 3. Writings and drawings were collected from the students' tasks during the lessons.

Class activity	Pretest	Lesson 1	Lesson 2	Lesson 3	Lesson 4	Lesson 5	Lesson 6	Post-test
Data from all students	Writings and drawings							
Data from select students	Interview 1			Interview 2				Interview 3

8. Think about a magnet and a steel nail.
 - a. Make a drawing to explain how the nail is attracted to the magnet.

- b. Now make a drawing to explain what would happen if you turned the nail around.

Figure 1. An example of the test questions.

Embedded assessments. In an integral component of our instructional design, students were frequently asked to reflect upon and explain, either in writing and/or by drawing, their interpretation of their experiences during their investigations about magnets. Assessments were designed to elicit core concepts in students' mental models in multiple ways throughout instruction, so that patterns or changes in students' emerging mental models could be described. For example, students were asked prior to and at key points during instruction to draw and describe how they believed a magnetized nail might be different from a nail that is not magnetized, the goal of which was to track emerging concepts and these concepts' relationships of internal organization, polarity, the nature of fields and the probability and consequences of magnetic interactions. These assessments also provided us with information about the validity of our results; the students' understanding of the task would be questionable if the students' drawings and descriptions generally shared no similarities with their prior versions.

The concept of a magnet interacting with another magnetic object was a primary focus of our research. It was addressed multiple times in embedded assessments throughout instruction. As an example, after an investigation in which students magnetized a wire and cut it into segments, they were asked to draw and explain the difference in nature between a magnetized and non-magnetized wire, an analogue to the nail which they had explored previously.

Interviews. Four students were selected from among the student sample to participate in semi-structured interviews. The interviewed students were purposefully selected by the researchers and

cooperating teacher based on a review of pretest responses. We aimed to choose responses that represented a range of ability and ways of expression and included differing interpretations (models) of magnetism. The audio-recorded interviews were conducted after the pretest, once midway through instruction and again after the post-test. The interviews ranged from approximately 5 to 10 minutes in length and were conducted by three authors of the paper. The interviews were conducted in an informal setting, in an open workspace area adjacent to the classroom. The interviews were transcribed verbatim and translated by the Finnish-speaking authors. All names given in the text are pseudonyms.

Interviews provided a way for students to elaborate on meaningful details regarding the pretest, post-test, and assessment responses that the students had written or drawn. Additionally, interviewing provided a mechanism by which researchers could confirm their interpretations of students' explanations and drawings with the students' intended meaning. For example, when students included the symbols + and – in their drawings, researchers asked them to explain these, avoiding leading terms such as “charge” so as not to bias the students' responses. Action arrows, waves, various representations of fields, causes and consequences of interactions, and clarification of vocabulary were also fertile areas for questioning. Most often, students were asked to elaborate on or explain features of their responses.

Data Analysis

All of the students' drawings and translated explanations and comments were compiled into a spreadsheet to facilitate comparison and for ease of electronically transmitting iterations of translation and coding. In the first level of the analysis, researchers used a constant comparative method of analysis (Patton, 2002) to code and categorize salient pre- and post-test features of students' mental models of (a) what a magnet is, (b) how a magnet “works” and (c) the physical, internal and external characteristics of a magnet and what it means to “be magnetized”. A keyword rubric piloted in two previous studies (Sederberg, Latvala, Lindell, Bryan, & Viiri, 2010; Sederberg & Bryan, 2010) was used in the coding process, in which the students' mental models were searched for underlying predicates and associated arguments (Finley, 1986). The keyword rubric had five main categories: Physical characteristics, Action and interactions, Two-sided behaviour, Alignment and Field concept.

The keyword rubric allowed us to categorize students' pre- and post-test mental models of magnets based on students' criteria for what a magnet is, how a magnet works and the characteristics that magnets share. The categories are based on references to charge and descriptions of poles, fields and structure (e.g. domains), expressed either in written explanation or drawing. Transcribed data from audio-recorded interviews added valuable insight into the interpretation of students' drawings as well as in-depth insight into their logic and thought process. Accordingly, six categories of students' mental models of magnetism emerged which served as a reference framework for tracking changes in mental models during instruction, which will be discussed in the following section.

Reliability and validity. As mentioned in the design of the study, the availability of both written, drawn and interview data helped to ensure that our interpretation of the students' models was close to what they intended to convey with the expressed model. We chose students to interview who held different models of magnetism initially, so that we could gain a detailed understanding of each type of model and ensure equal treatment of the model types. For example, the drawings were sometimes open to interpretation about whether the polarity in the drawing was charge-based or otherwise. The interview helped us clarify whether the student was thinking of electricity or magnetism. This analysis exposed nuances in language and terminology with students' use of everyday language in the description and discussion of their experiences in a scientific context. As an example, the students often used the Finnish word “merkki” to distinguish between ends of a magnet. When used in electricity or mathematic lessons, the word denotes “sign”, for example positive and negative charges or numerical values. In everyday language, however, it can also be used as the word “marking” or “label”. From interviewing the students, we had the basis to decide that unless confirmed by other sentences or drawings referring to charges, we did not assume the student to be thinking of charges when using the word “merkki”.

Another decision we made during the analysis was about describing the composition and structural organization of ferromagnetic materials. The Finnish students commonly use the term “alkeismagneetti”. This word, translated into English as “minimagnet,” has a broader implication of an essence or starting material, a “protomagnet”, akin to what a chemical element is to matter. Students used the term in the context of alignment, that is being aligned or organized when a material is magnetized and unaligned or disorganized when it is not. We used the analogous and more scientifically normative term “domain” for this characteristic.

The coding and categorizing of the data were initially performed by one of the authors, and the codings were revised and a new division of categories (regarding the domain model types) was agreed upon after a detailed discussion on the data amongst three authors. The whole coding process was not remade after the authors gained agreement on the categorization of the data, as the data items were few.

As Norman (1983, p. 11) laments, “People may state (and actually believe) that they believe one thing but act in quite a different manner”. For this reason, it should be remembered that all data and interpretations pertaining to student mental models are just that, interpretations. They are informative for the design of teaching sequences or other purposes that rely on knowledge about how a group of people tends to think about something (such as magnetism).

RESULTS

Our findings are presented in two parts. In the first part, we present the range of students’ mental models of magnetism that emerged from our analysis of data, prior to and following instruction. We then present when and how, during instruction, the characteristics and conceptual sophistication of the students’ models of magnetism changed.

Nature of Finnish Secondary School Students’ Mental Models in Magnetism Prior to and Following the Instruction

A description of the six mental model categories we used in our analysis is presented in Table 3.

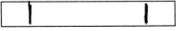
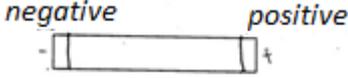
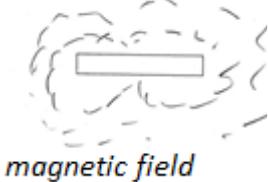
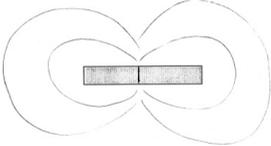
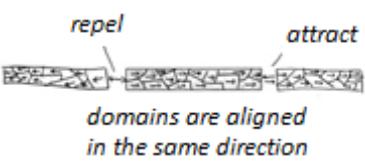
Students’ pre-instruction mental models of magnets tended to be based on describing magnets in concrete ways, for example, by shape, colour, having opposite ends or sides, and by observed effects on other objects, such as “attracts” or “catches onto.” The two-sided character of magnets was characteristically described by students in terms of the symbols + and – or by colour.

Some students explicitly refer to charge terminology in their mental models of the polar nature of magnets. For example, Sofia wrote in defining a magnet, “It’s a + or – charged piece. The + or – draw each other towards themselves, and the same sides repel.” Eight of the 12 students’ pretest mental models of magnets included representations suggesting electric charge to designate the polar nature of a magnet, as illustrated by the examples in Table 3 (Olav). None of the students used the traditional north/south terminology in their mental models prior to instruction.

Students often incorporated the polar nature of permanent magnets in their mental models of how magnets work. For example, two students, Charles and Victor, maintained through instruction and on the post-test the “opposites attract” mental model, in which one end of a magnet always attracts, the other always repels, even though they performed experiments in which they observed nails and wires consistently attracted to both poles or ends of the magnet.

Three students maintained the position that the nail would be attracted to both sides of the magnet the same way, although they revised their mental models of the mechanism by which this occurs. Each of these initial models was grounded in the explicit or implied representation of charge.

Table 3. Six categories of students' initial and final mental models.

	Model	Criteria	Examples	
Models indicative of pretest responses	Pole model	Reference to different ends, halves or sides, or specifically, poles.		"Magnet attracts metal and other magnets towards it, but the magnets have to be of different ends, otherwise they will repel each other" (Charles, pretest).
	Charge model	Reference to charge, positives, negatives, use of charge symbols (+ or -) in drawings.		"The shape of the magnet can be anything, but the magnet always has a + or - pole. The - and + attract each other, unlike the - and - or + and +, those repel" (Olav, pretest).
	Field model	Reference to magnetic field acting on other objects, such as a compass.		"A magnet has a magnetic field that attracts metals" (John, pretest).
Models representative of post-test responses	Pole/field model	Reference to polarity of a magnet and to its magnetic field acting on other objects.		"A magnet has two poles that repel the same sign pole if another magnet is brought near" (Charles, post-test).
	Pole/domain model	Reference to domains and alignment with an "opposites attract" explanation of interactions.		"A magnet has a south and a north pole. Poles of the same sign repel each other, and different signs attract... Domains are aligned in the same direction" (Sofia, post-test).
	Field/domain model	Reference to domains and alignment, implying the formation of a field able to affect other objects.		"Domains are organized, the magnet is surrounded by a magnetic field" (Emely, post-test).

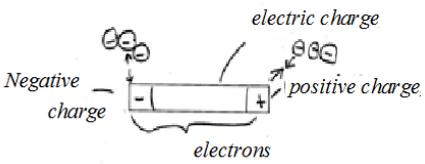
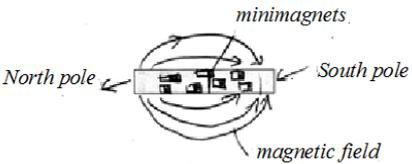
Peter, for example wrote in the pretest that "Nail has negative and positive charges, so both ends of the magnet will attract it" and in the post-test that "The domains in the nail are reorganized so that the magnet will attract them." Peter refers to organization of the domains in the nail, recognizing that the organization of the domains is relative to the pole of the magnet.

As we will discuss in what follows, those students (9 out of 12) whose initial mental models of magnets were grounded in elements of charge were the most likely to revise their models towards more normative scientific views. The three students (Charles, John and Matt) whose initial mental models were not grounded in charge tended to be more constrained by their existing models.

Six of the 12 students in our sample revised their initial mental models towards more normative and scientific mental models by incorporating the concept of the alignment and re-alignment of domains into their explanations of what it means to be magnetized and how magnets work. Furthermore, students' mental models following instruction were more likely to be based on inner structure and agency (a magnet or magnetized object inducing a change in another object), commonly referring to the concepts of alignment, domains and citing the effect that magnets can have on objects with which they interact (e.g. affecting a compass or a nail). Post-instruction mental models were also more likely to characterize magnetized versus non-magnetized states of matter and allude to a field as a consequence of being magnetized.

Jenny's pre- and post-test responses exemplified the contrast in the level of sophistication of pre- and post-instruction mental models of what a magnet is and how a magnet works (Table 4). Her model demonstrates significant revisions, not only in fundamental concepts, such as what it means to be magnetized, but also in nuances that were not explicitly addressed in instruction. As examples, she elaborated that magnets can be different strengths and, when cut into pieces, become smaller magnets as well as how a compass could be used to illustrate the nature of the magnetic field.

Table 4. Jenny's pre- and post-test mental models of magnets and how magnets work.

	Pretest	Post-test
Definition of a magnet	<i>It has two ends + and -. There are different kinds of magnets and also of some sort of magnetic powder. There are bar magnets and some horseshoe-shaped ones also.</i>	<i>Inside the magnet, there are domains/so-called "minimagnets" that align when the object magnetizes. The north and south poles of the magnet attract each other... Magnets are of different strengths and can be cut into smaller magnets.</i>
Characteristics of a magnet	 <p>The diagram shows a rectangular bar magnet with a minus sign (-) on the left end and a plus sign (+) on the right end. Above the left end are three circles with minus signs, labeled "Negative charge". Above the right end are three circles with plus signs, labeled "positive charge". Below the bar, a bracket spans the width and is labeled "electrons".</p>	 <p>The diagram shows a rectangular bar magnet with a "North pole" on the left and a "South pole" on the right. Inside the magnet, several small rectangles represent "minimagnets", each with a north-south axis. Curved arrows around the magnet represent the "magnetic field", pointing from the North pole to the South pole.</p>
How a magnet works	<i>It attracts other metal objects that have a charge different from that of the pole that the other object is being tried to touch with. If two minus poles are tried to get together, they will repel each other.</i>	<i>For example, a compass can be used to demonstrate the poles and field of the magnet. The lines go from north pole to south pole. Magnets can also be cut in half and it still becomes a new magnet.</i>

While the models (Figure 2) progress in a trend from more non-normative to more normative scientific models, we are not implying amongst them an imposed order of progression or sophistication. They merely serve to illustrate the categories of our sample of students' pre- and post-instruction mental models of the characteristics of magnets and how magnets work. Figure 2 connects the initial and final mental model categories for each student in our sample, tracing a "before and after" trajectory from their mental model prior to and following instruction.

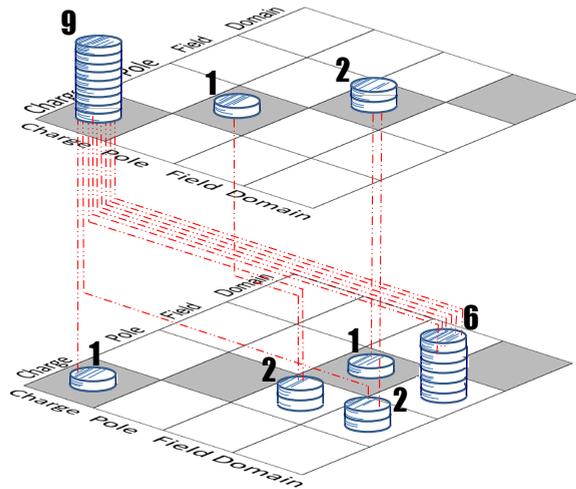


Figure 2: Comparison of students' mental models before instruction (top) and after instruction (bottom).

Figure 2 depicts a two-layer two-dimensional array using four criteria, charge, pole, field and domain, each representing identified elements common to the defined mental model categories (see Table 3). At each category, the students are represented as disks at the respective position. As an example, prior to instruction, nine students' mental models were categorized as charge models, one student's as a pole model, and two students' as field models. Thus, each student's initial mental model was based on a single dimension or element. By comparison, students' mental models following instruction were more likely to be multidimensional. For example, two students' final mental models were classified as pole/field, characterized by attributes of both elements, with two students' mental models classified as pole/domain models. Six students' mental models following instruction were categorized as field/domain models. An interesting observation from Figure 2 is that the only students whose final mental models achieved field/domain status were those whose mental models prior to instruction were based on elements of charge.

Students' initial mental models of magnets and magnetic behaviour focused on concrete observations, for example identifying alternate ends or sides and describing interactions in terms of "attracts" or "catching onto." Internal composition was limited to defining the two-sided characteristic rather than to account for the process of how and why objects are magnetized, and descriptions of interactions were oriented towards attraction. Students did not include repulsion among their mental model representations. Their post-instruction mental models were much more likely to include internal structure related to magnetizing and demagnetizing as well as the magnetic field and being able to have an effect on another object as a consequence of being magnetized.

When and How do Content and Conceptual Sophistication of Students' Models of Magnetism Change During the Course of Instruction?

The six categories of mental models described above served as a template against which we were able to characterize students' revisions of their mental models. The most dramatic conceptual revisions in students' mental models of magnets that occurred were related to the following concepts:

1. the "two-sidedness" or polar nature of magnets and magnetized objects,
2. the presence and effects of the magnetic field (magnetic interactions) and
3. the internal structure and organization; in other words, what it means to "be magnetized."

Most significantly, some students were able to use these three themes in support of each other towards developing mental models that were more normative in nature.

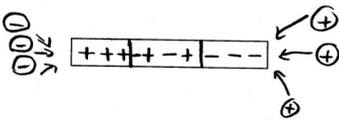
Mental models of “two-sidedness”: Magnetic poles. Students’ initial and emerging mental models represented the polar nature of magnets and magnetized objects in several ways, the most common of which used symbols related to mathematical sign or electric charge (+/-). Amongst the eight students whose initial mental models represented poles as charges (see Figure 2), only one (Olav) used pole charges in his final model.

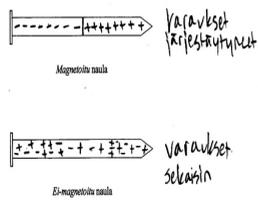
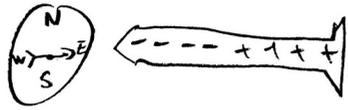
While for the purpose of classification of categories of students’ mental models we grouped those including sign symbols as charge-based models, we recognize in interpretation a disparity between what we might consider charge in a traditional electrical sense and students’ intended meaning. For example, Sofia’s initial mental model of a magnet included poles indicated by signs, which she elaborated in interview: “It’s a positively or negatively charged piece”. In continued questioning about the meaning of these symbols, Sofia explained, “I’m not sure, I just felt that there’s, like, two sides in the magnet, and they are different”. Thus, while Sofia uses the symbols and literal use of the word “charge”, she may be applying familiar terminology from other contexts in a way that makes sense to her in describing the polar characteristic of magnets. As we pointed out earlier, the Finnish word some students used in explaining representations of their mental models in fact implies “label” or “marking” in some contexts. At 15 years of age, children are familiar with the +/- notation in the mathematical sense and, in general, where two-sidedness is distinguished, for example in the case of batteries.

Further, as we will discuss in the following section, assigning familiar signs to the poles of magnets allows students to make sense of magnetic interactions, as Sofia elaborated in interview: “The plus and minus come together”. We found multiple examples of students combining scientific and everyday terminology in revising their mental models in trying to make sense of what they were learning. For example, some students used the phrase “magnetically charged” to indicate that an object had been magnetized.

Table 5 shows the trajectory of one student’s drawings and explanations, indicative of his concept of poles in his mental model of magnets and magnetized objects during instruction. Depictions of poles are drawn from students’ mental models revealed in the pretest questions and in embedded assessments, which were carried out throughout instruction. These assessments provided multiple opportunities for students to reconsider and express their emerging mental models as well as providing a means of triangulation for our analysis.

Table 5. One example trajectory of mental models based on poles.

Peter	
Pretest magnet	 <p>“Magnet pulls opposite charges towards itself, + pulls a -, and - pulls a plus.”</p>

<p>Magnetized and non-magnetized nails (after investigation 2)</p>	 <p style="text-align: center;">"Charges are ordered; Charges are mixed."</p>
<p>Magnetized nail and compass (after investigation 3)</p>	 <p style="text-align: center;">"The negative charges of the nail draw the compass needle's positive charges towards it."</p>
<p>Magnetized wire cut into pieces (after investigation 5)</p>	<p style="text-align: center;">P—E P—E P—E P—E</p> <p style="text-align: center;">N—S N—S N—S N—S</p>
<p>Post-test magnet</p>	 <p style="text-align: center;">"Magnet has a north and south pole. It has its own magnetic field (broken line). It is full of minimagnets."</p>

Mental models of magnetic fields: The basis for interaction. We introduced the compass in the first lesson as a detector for the magnitude and direction of the forces exerted in the magnetic field. Prior to the magnetic field investigation (lesson 3), few students' mental models represented the effect or presence of a magnetic field. When they did, they typically represented the concept of the magnetic field as action arrows between the end of a magnet and another object.

Students' initial mental models of magnetic interactions were most often based on the dichotomous "one end attracts, the other end repels". Sofia explained her representation in her pretest interview (Figure 3).

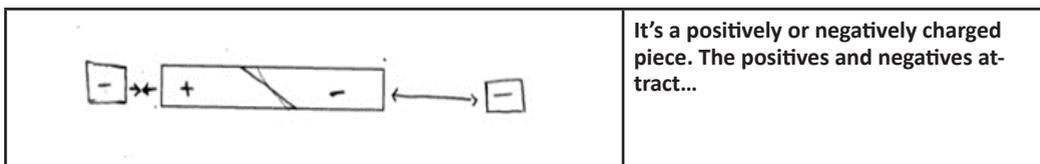


Figure 3. Sofia's pretest answer on how a magnet attracts a nail and her interview clarification.

As an example of students' mental models in transition, following instruction, Sofia explained her model of magnetic interactions, having adopted the terminology of poles but retaining sign: "A magnet has a south and north pole. Poles of the same sign repel each other, and different signs [attract]."

A critical component in arriving at the field model seemed to be the interpretation of the interactions between compasses and magnets. Those students who used either the compass as a measure of the “*range of the magnetic field*” (Ann, lesson 5) or the strength of a magnet also progressed to using the magnetic field as an explanation of phenomena. One complex situation that students were invited to explain with their model, in lesson 6, was the effect of a magnet on a magnetic fluid: ferrofluid. Three students in our sample (Ann, Alex and Peter) used the concept of a magnetic field to give a scientifically normative explanation of the behaviour of ferrofluid.

Students’ mental models of the mechanism by which the interactions occurred between a magnet and a nail became more sophisticated after each of the investigations. However, of the eight students who were present and responded to both the pre- and post-test assessments, only one of the students (Victor) changed their positions for attracting and repelling, understanding following instruction that a nail is always attracted to either pole of a magnet (from “attract/repel” to “attract/attract”) (see Table 6).

Table 6. Pre- post comparison of interactions between a magnet and nail (Question 8 in Figure 1).

	Pretest magnet model	Pretest	Post-test magnet model	Post-test
Ann	Charge	Attract/repel	Field/domain	Attract/repel
Charles	Pole	Attract/Non-rep	Pole/field	No reply
Victor	Charge	Attract/repel	Pole/field	Attract/attract
John	Field	Non-rep	Field	Attract/attract
Matt	Field	Attract/repel	Pole/domain	Attract/repel
Sofia	Charge	Attract/attract	Pole/domain	Attract/attract
Alex	Charge	Attract/attract	Field/domain	Attract/attract
Olav	Charge	Attract/repel	Static charge	Attract/No reply
Emely	Charge	Attract/repel	Field/domain	Attract/repel
Peter	Charge	Attract/attract	Field/domain	Attract/attract
Thomas	(Absent)	(Absent)	Field/domain	Attract/attract
Jenny	Charge	Attract/attract	Field/domain	Attract/repel

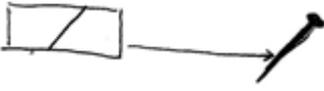
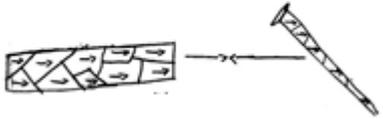
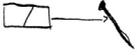
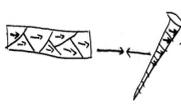
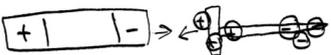
Table 6 also illustrates the stability of existing mental models inasmuch as three students (Ann, Matt and Emely) maintained their positions that one end or pole of a magnet attracts while the other end repels.

Mental models of internal structure and organization: “Being magnetized”. The concept and consequences of alignment within magnetic materials formed a major focus for our challenging of students’ mental models of how magnetic interactions occur. Specifically, we wanted to know how students’ mental models reflected (a) what happens to the nail when it comes near a magnet, (b) if and why the nail could also be considered a magnet and (c) a mechanism that could explain how the nail could be alternately attracted to either end of a magnet.

There are two ways in which the concept of organization and alignment appear in students’ mental models of magnetic materials. The first is the concept of mixing. Emely, for example, after magnetizing and cutting a wire in investigation 5, offers his account of how dropping a wire might demagnetize it: “*magnetivity can be lost by shaking, domains mix.*” Ann explains in a more scientifically normative way, on an assessment midway through the unit asking her to predict the effect of heating a mag-

netized object: "...by heating, the directionality of the domains mix." Similarly, on her post-test, "If the domains are not aligned, the object no longer has a magnetic field." Thus, Ann has modified her mental model of magnets and magnetic interactions, taking into account the alignment of domains and the effect that this has on the formation of the magnetic field.

Table 7. Pre- and post-test comparison of interaction between magnet and nail.

	Pretest	Post-test
Sofia	 <p>"Magnet attracts the nail."</p>	 <p>"The magnet attracts the nail to itself."</p>
	 <p>ei tapahtu mitään</p> <p>"Nothing different happens."</p>	 <p>koska naula kääntyy alkaismagneetti kääntyyvät myös hyöriin osittain</p> <p>"The nail is turned, the domains also turn to a good position."</p>
Jenny	 <p>ne vetää toisiaan puoleensa ja siirtyy elektroneja</p> <p>"They attract each other, and electrons are transferred."</p>	 <p>ne hylkii toisiaan</p> <p>"They repel each other."</p>
		

The majority of the students who revised their mental models to include an internal organization (alignment of domains) concept were consistent in their understanding of whether or not the nail can be repelled by a magnet. The cases in Table 7 are representative of the range of pre- and post-test mental models that emerged.

What is significant among the final mental models of these students is the representation of agency, the magnet inducing a change in the internal structure of the nail, either in the form of mini-magnet-like domains, or as arrows, used in instruction to represent magnetic moments.

DISCUSSION AND CONCLUSION

Nature of Finnish Students' Mental Models of Magnetism

We found six categories for the nature of students' mental models of magnetism. Four of those, the charge model, field model, pole/domain model and field/domain models, are similar to the models that Borges and Gilbert (1998) reported among secondary students, technical school students, physics teachers, engineers and practitioners whose daily jobs are related to electricity and electromagnetism. In these authors' report, these models were called, respectively, magnetism as electricity, magnetism as a cloud, magnetism as electric polarization and the field model. The fifth model found by Borges and Gilbert, magnetism as pulling, we do not recognize in our sample. None of the models considered magnetism as an intrinsic property of magnets without any further explanations. We also discussed the name "pulling" in the model, as two students out of twelve in our sample maintained, through instruction and on the post-test, the mental model of an object (like a nail) being attracted to one end of a magnet but being repelled by the other.

Instead, we found two new categories of models: the pole model and pole/field model. The pole model differs from our other categories in that this model has a reference to different ends, halves or sides but does not refer to charge nor any other attributes of the magnets. The field/pole model differs from our field model in such a way that in addition to distance interaction, it also refers to the polarity of a magnet. We consider these distinctions important in understanding pupils' thinking about the key concepts of magnetism: structure and organization, magnetic fields and magnetic interactions.

Change of Content and Conceptual Sophistication of Students' Models of Magnetism During the Instruction

Students' models of magnetism became more normative and scientific, including more attributes of magnetism to explain the phenomena inquired about as the course proceeded. The critical moments happened during investigations 3, 5 and 6 for understanding magnetic fields and during investigation 5 for understanding magnetic domains. In another study using the same teaching materials, it was discovered that inquiring about compasses (investigation 3) and about cutting magnets (investigation 5) was a prerequisite for students' model development (Harmoinen, 2013).

The initial mental models of magnets of nine of the 12 students in our sample were based on charges (see Table 6.). We are intrigued by the result that for these students, the final field/domain model, the one most closely aligned to a normative scientific understanding, was only accessed from a path from a charge-based model. Conversely, eight of the nine students whose initial models involved charge transitioned to the field/domain model. One plausible explanation may be that some of these students had previously learned about electricity and electric fields; another may be that their existing mental model of mobile charges in magnets and in magnetizing may have supported learning about the reversible nature of the alignment of domains, both of which are internal mechanisms. Still, these students' mental models of charge appear to have facilitated revision more than others. Meaningful learning occurs when learners are able to incorporate new knowledge into an existing framework (Ausubel, 1968). It could be that the reversibility of charged-based mental models provided a framework for students that facilitated the accommodation of the tentative nature of domain alignment. The sophistication of some of these students' initial charge-based mental models may have provided the framework for the incorporation of the domain concept in a meaningful way. For example, in Peter's pretest account of how a nail is attracted to the magnet, regardless of the way the nail is turned, he explained, "The nail is neutral. The nail has + and - . The charges arrange in the nail again when the negative end of the magnet is brought near the nail." He then wrote, "Charges are reorganized, and the magnet still attracts the nail." Making the transition from charges reversing to domains realigning may be a meaningful trajectory for some students.

The concept of poles commonly accompanies models of charge, because they can be used interchangeably to explain the two-ended behaviour of magnets; one attracts, the opposite repels. As we found, students may also incorporate an "opposites attract and likes repel" paradigm into their men-

tal models of the interaction between a magnet and another magnetic object. Children also refer to + and – in the sense that they are signs that represent action; the + pole is the one that attracts, and the pole with the – sign is the repelling pole (Sederberg, 2012). One of the reasons for the robust nature of the “opposites attract” model may be its pragmatic approach to explaining dichotomous interactions in everyday encounters (up-down, true-false, in-out, etc.).

Students who used minimagnets in their drawings most likely did so because of a textbook illustration shown to the class. One of the “tells” in the minimagnet explanations is about non-magnetized objects or demagnetizing. Some students wrote that the minimagnets are “mixed” within the magnet (“sekoittaa” is “to mix”, as in mixing ingredients for a cake), and this lends itself to a model where small magnets float around in a generic “mix”. This begs the question that if you mix or magnetize them, they will move physically around, much like charges when “magnetized.” Other aspects of the “minimagnet model” do seem to agree with the domain model, for example the “magnetic directionality” of the domains. Still, “the minimagnets mix” and never “the directions of the minimagnets mix” again cause a question of students’ understanding of the domain concept as a component of their mental models of how magnetic interactions occur.

What Hinders Revisions in Mental Models?

Students whose initial mental models of magnets included charges tended to maintain those models even after conducting an investigation designed to help learn to distinguish between them. At first glance, this may seem disappointing for an educator. Still, we would posit that even though students drew models of magnetized and non-magnetized nails differing only in the distributions of internal charges, they were “on the hunt” for a more explanatory model. In our observations, students appeared perplexed when investigating the effects of a charged rod and a magnetized nail against a compass. Some groups repeatedly tried to get the rod to affect a paper clip. Some students concluded from this discrepant event that the reason they observed no interaction was that the paper clip was too large. In the end, it may be that at the cusp of a potentially more sophisticated and explanatory mental model, students revert to a previous simpler mental model with which they are comfortable. Research has shown, for example, that students prefer concrete or simpler models, and although they may have been exposed to more abstract models with greater explanatory power, they instead try to accommodate new knowledge by incorporating it into previously constructed mental models, the simple model being the more reasonable (Stefani & Tsapalis, 2009). Building upon on this finding, it makes sense for students to use electricity as a starting point in explaining magnetic properties. It would be interesting to study whether a similar process would exist if the students had inquired into magnetism first.

A critical point in understanding magnetic domains and fields for many of the students occurred in investigations 4 and 5, making a straw magnet and magnetizing and cutting a wire, both designed to help students to incorporate the concepts of alignment and magnetic domains. Making a connection between the alignment of the iron filings in her straw magnet, the magnetic field, and being magnetized, Jenny explained in interview, “Here when it was magnetic, it has that magnetic field there around it, so that it went from one end to another. And then you shook it, then they [compass arrows] no longer were like that, but they just went there in unison, pointing to the north [pole of the Earth].”

Interpretation Issues

In a complementary way, students’ drawings, written explanations and interview responses, as separate data sources, provided us a window into the detail, sophistication and explanatory power of these students’ mental models that would not have been possible from any one source alone. Responses to these different formats of assessment also revealed that the type of question plays a role in the nature of the response. For example, a student’s explanation may refer to the alignment of domains in a written explanation, but their drawing may not, or they may provide very detailed drawings of the alignment of domains and field lines and even show the effect on a nearby object, but merely explain in writing that magnets have poles and can attract things. In interview, for example, Victor comments

about his drawing of his magnetized straw magnet: “There would also be these [lines] outside, but I didn’t draw them in, but the fields are there also.” Thus, Victor actually knew more than what he thought was necessary to initially answer the question.

Some students may be self-conscious about their ability to draw well; others may view the opportunity as an artistic way of expression. Struggling with words, not knowing the accepted (or expected) word and hesitating in fear of using the wrong word may impede students’ descriptions as well as interview responses. The difficulty often may be not in the interpretation of phenomena or experimental results, but rather in finding a way to describe them (Johnson, 1999). As an example, Sofia referred to domains in a magnetized nail as being in a “good position” rather than their being aligned.

This research should be of interest to science educators, teachers and curriculum developers who are interested in student learning, mental models and learning trajectories, both in a general science context and within the context of the content domain of magnetism. There is ample evidence that the abstract nature of magnetic phenomena poses uncommon challenges for learners of all ages and that even after repeated study across multiple grades, many robust and non-normative concepts perpetuate people’s (even teachers’) conceptions about magnetism (Atwood, Christopher, & McNall, 2007; Atwood, Christopher, Combs, & Roland, 2010; Barrow, 1987; Constantinou et al., 2001; Finley, 1986; Hickey & Schibeci, 1999). Knowledge of students’ mental models prior to and during instruction, such as those emerging from this research, will enable educators to “choose teaching activities which are more likely to be interpreted by students in the way intended” and to reject classical experiments which are often not interpreted by students in the ways they are intended to be (Driver, Guesne, & Tiberghien, 1985, p. 6–7).

REFERENCES

- Ainsworth, S., Prain, V., & Tytler, R. (2011). Drawing to learn in science. *Science*, 333, 1096–1097. doi:10.1126/science.1204153.
- Atwood, R. K., Christopher, J. E., & McNall, R. (2007, April). Are in-service elementary teachers prepared to teach fundamental concepts of magnetism and the behavior of magnets? Paper presented at the annual meeting of the National Association for Research in Science Teaching New Orleans, LA.
- Atwood, R. K., Christopher, J. E., Combs, R. K., & Roland, E. E. (2010). In-service elementary teachers’ understanding of magnetism concepts before and after non-traditional instruction. *Science Educator*, 19, 64–76.
- Ausubel, D. P. (1968). *Educational psychology: A cognitive view*. New York: Holt, Rinehart and Winston.
- Bar, V., Zinn, B., & Rubin, E. (1997). Children’s ideas about action at a distance. *International Journal of Science Education*, 19(10), 1137–1157.
- Barrow, L. H. (1987). Magnet concepts and elementary students’ misconceptions. In J. Novak (Ed.), *Proceedings of the Second International Seminar: Misconceptions and Educational Strategies in Science and Mathematics* (Vol. 3) (pp. 17–22). Ithaca, NY: Cornell University.
- Borges, A. T., & Gilbert, J. K. (1998). Models of magnetism. *International Journal of Science Education*, 20(3), 361–378. doi: 10.1080/0950069980200308
- Burgoon, J. N., Heddle, M. N. & Duran, E. (2010). Re-examining the similarities between teacher and student conceptions about physical science. *Journal of Science Teacher Education*, 22(2), 110–114.
- Cheng, M. F., & Brown, D. E. (2010). Conceptual resources in self-developed explanatory models: The importance of integrating conscious and intuitive knowledge. *International Journal of Science Education*, 32(17), 2367–2392.
- Clement, J. (1989). Learning via model construction and criticism: Protocol evidence on sources of creativity in Science. In J. Glover, R. Ronning, & C. Reynolds (Eds.), *Handbook of creativity*:

- Assessment, theory and research* (pp. 341–381). New York: Springer.
- Constantinou, C., Raftopoulos, A., & Spanoudis, G. (2001). Young children's construction of operational definitions in magnetism: The role of cognitive readiness and scaffolding the learning environment. In J. Moore & K. Stenning (Eds.), *Proceedings of the twenty-third annual conference of the Cognitive Science Society*. London: Routledge.
- Dove, J., Everett, L., & Preece, P. (1999). Exploring a hydrological concept through children's drawings. *International Journal of Science Education*, 21(5), 485–497. doi: 10.1080/095006999290534
- Driver, R. Guesne, E., & Tiberghien, A. (1985). *Children's ideas in science*. Philadelphia, PA: Open University Press.
- Driver, R., Asoko, H., Leach, J., Mortimer, E., & Scott, P. (1994). Constructing scientific knowledge in the classroom. *Educational Researcher*, 23(7), 5–12. <http://www.jstor.org/stable/1176933>
- Finley, F. N. (1986). Evaluating instruction: The complementary use of clinical interviews. *Journal of Research in Science Teaching*, 23(17), 635–650. doi: 10.1002/tea.3660230706
- Greca, I. M., & Moreira, M. A. (2002). Mental, physical, and mathematical models in the teaching and learning of physics. *Science Education*, 86(1), 106–121.
- Guisasola, J., Almudi, J., & Zubimendi, J. (2004). Difficulties in learning the introductory magnetic field theory in the first years of university. *Science Education*, 88(3), 443–464. doi: 10.1002/sci.10119
- Guth, J., & Pegg, J. (1994). First-year tertiary students' understandings of iron filing patterns around a magnet. *Research in Science Education*, 24(1), 137–146.
- Harmoinen, S. (2013). Opettajan ohjauksen ja vuorovaikutuksen antaman tuen merkitys oppilaiden rakentaessa mallia magnetismista. (Doctoral dissertation, University of Jyväskylä, Jyväskylä, Finland). Retrieved from <https://jyx.jyu.fi/handle/123456789/41997>.
- Haupt, G. W. (1952). Concepts of magnetism held by elementary school children. *Science Education*, 36(3), 162–168.
- Hickey, R., & Schibeci, R. (1999). The attraction of magnetism. *Physics Education*, 34(6), 383–388. doi:10.1088/0031-9120/34/6/408
- Johnson, A. (1999). *Students' development of models of magnetic materials, patterns of group activity, and social norms in a physics classroom* (Unpublished dissertation). San Diego State University and the University of California, San Diego.
- Johnson-Laird, P. N. (1983). *Mental models*. Cambridge: Cambridge University Press.
- Lehrer, R. (2009). Designing to develop disciplinary dispositions: Modeling natural systems. *American Psychologist*, 64(8), 759–771. doi: 10.1037/a0017274
- Maloney, D. P. (1985). Charged poles? *Physics Education*, 20(6), 310–316.
- Maloney, D. P., O'Kuma, T. L., Hieggelke, C. J., & Van Heuvelen, A. (2001). Surveying students' conceptual knowledge of electricity and magnetism. *American Journal of Physics*, 69(S1), S12–S23.
- Olson, J. K. (2008). The science representation continuum. *Science and Children*, 46(1), 52.
- Norman, D. A. (1983). Some observations on mental models. In D. Gentner & A. L. Stevens (Eds.), *Mental models* (pp. 7–14). Hillsdale, NJ: Erlbaum.
- Patton, M. Q. (2002). *Qualitative evaluation and research and evaluation methods*. Thousand Oaks: Sage Publications.
- Ravanis, K., Pantidos, P., & Vitoratos, E. (2010). Mental representations of ninth grade students: The case of the properties of the magnetic field. *Journal of Baltic Science Education*, 9(1), 50–60. Retrieved from <http://journals.indexcopernicus.com/abstracted.php?level=5&icid=907735>
- Rennie, L. J., & Jarvis, T. (1995). Children's choice of drawings to communicate their ideas about technology. *Research in Science Education*, 25(3), 239–252. <https://doi.org/10.1007/BF02357399>
- Sederberg, D., & Bryan, L. (2009). *Tracing a prospective learning progression for magnetism with implications at the nanoscale*. Proceedings of the Learning Progressions in Science (LeaPS) Conference (<http://www.education.uiowa.edu/projects/leaps/proceedings/>). Iowa City, IA: Learning Progressions in Science.

- Sederberg, D., & Bryan, L. (2010, July). *Magnetism as a size dependent property: A cognitive sequence for learning about magnetism as an introduction to nanoscale science for middle and high school students*. Paper presented the International Conference for the Learning Science, Chicago, IL.
- Sederberg, D., Latvala, A., Lindell, A., Bryan, L., & Viiri, J., (2010, August). *Progressions of students' mental models of magnetism across scale*. Presentation at the annual conference of Groupe International de Recherche sur l'Enseignement de la Physique (GIREP, International Research Group on Physics Teaching). Reims, France.
- Sederberg, D. (2012). *Middle school students' mental models of magnets and magnetism* (Doctoral dissertation, Purdue University).
- Stefani, C., & Tsapalis, G. (2009). Students' levels of explanations, models, and misconceptions in basic quantum chemistry: A phenomenographic study. *Journal of Research in Science Teaching*, 46(5), 520–536. doi: 10.1002/tea.20279
- Stepans, J. (1994). *Targeting students' science misconceptions: Physical science activities using the conceptual change model*. Riverview, FL: Idea Factory, Inc.
- Tytler, R., Prain, V., Hubber, P., & Waldrip, B. (2013). *Constructing representations to learn in science*. Springer Science & Business Media.
- Wiggins, G. & McTighe, J. (2006). *Understanding by design*. Alexandria, VA: Association for Supervision and Curriculum Development.