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Atwood's Machine and Electromagnetic Induction: A Real Quantitative Experiment to Analyze Students' Ways of Reasoning

Giacomo Bozzo [1], Marisa Michelini [2], Assunta Bonanno [3], Alberto Stefanel [2*]

[1] Secondary School "G.B. Quadri", Vicenza, ITALY
[2] Department of Mathematics, Computer Science and Physics, University of Udine, Udine, ITALY
[3] Department of Biology, Ecology and Earth Sciences, University of Calabria, Cosenza, ITALY

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Abstract

We report a research-based proposal on electromagnetic induction within the theoretical framework of the Model of Educational Reconstruction. The proposal is based on a sequence of inquiry-based experimental activities centered on hands-on materials and *Real-Time* quantitative experiments, through which students explore the phenomenology of electromagnetic induction. The sequence was planned to address Faraday-Neumann-Lenz law analyzing the involved physics quantities and constructing quantitative relationships between them. Our hypothesis was based on the idea that phenomenological explorations performed through online sensors promote a functional understanding of electromagnetic induction and help students to face the conceptual knots highlighted by international literature about these phenomena.

The educational sequence was proposed to a sample of 87 high school students with the aim of analyzing the evolution of the educational processes employing a set of inquiry-based tutorials. The qualitative analysis of students' answers demonstrates that students increased their knowledges in the analysis of electromagnetic induction phenomena recognizing the fundamental role of time-variation of the magnetic field flux in the Faraday-Neumann-Lenz law.

Keywords: electromagnetic induction, Faraday-Neumann-Lenz law, magnetic field lines, flux of magnetic field, real-time lab

INTRODUCTION

Electromagnetic induction (EMI hereafter) plays a crucial role in different physics phenomena (Galili, 2001; Galili & Kaplan, 1997; Kesonen et al., 2011; Scanlon et al., 1969; Zuza et al., 2012) and represents a fundamental prerequisite for understanding many domains of modern physics, as for example superconductivity (Greczyło et al., 2010; Kedzierska et al., 2010) and Special Relativity (Galili & Kaplan, 1997; Galili et al., 2006). Moreover, EMI plays a crucial role for a great number of technological applications (Dori & Balchner, 2005) that are used in everyday life and that are present (in different forms) in almost all didactic laboratories (Dori & Balchner, 2005; Fodor & Peppard, 2012; Jodl & Eckert, 1998; McNeil, 2004; Priest & Wade, 1992; Torzo et al., 1987). In many cases, the educational applications of Faraday-Neumann-Lenz law (FNL law hereafter) are particularly suited to introduce and explain the processes of energy transformations, which represent very important topics both from social and economic viewpoints (Dori & Balchner, 2005; Härtel & IPN Group, 1986; McDermott & Shaffer, 1998). Despite its educational and social relevance, different studies in physics education have highlighted various learners' difficulties in the comprehension of EMI and FNL law and have demonstrated how the involved concepts and models are particularly problematic for students (as for example: Bagno & Eylon, 1997; Duit et al., 1985; Maloney et al., 2001; Sanchez & Loverude, 2012; Secrest & Novodvorsky, 2005; Thong & Gunstone, 2008). The related concepts *"are highly abstract and their understanding is dependent on models"* (Guisasola et al.,

✉ giacomo.bozzo@unical.it ✉ marisa.michelini@uniud.it ✉ assunta.bonanno@unical.it
✉ alberto.stefanel@uniud.it **(*Correspondence)**

Contribution to the literature

- The research based educational path on electromagnetic induction, designed in the framework of Model of Educational Reconstruction, aims to construct a functional understanding of electromagnetic induction, overcoming the learning knots discussed in literature about this topic.
- The electromagnetic Atwood's machine based on on-line sensors focus student on the role of time and parameters affecting Faraday-Neumann-Lenz law.
- The student learning outcomes show the role of these experiments for understanding the importance of variation in time of the flux in Faraday-Neumann-Lenz law.

2008; see also Albe et al. 2001; Huang et al., 2008; Sanchez & Loverude, 2012).

It is important to build a functional understanding of key concepts (as for example the concepts of flux and its time variation) related to EMI (McDermott, 1991; Belcher & Olbert, 2003; Jelicic et al., 2017) that make it possible to describe electromagnetic phenomena and in particular FNL law starting from experimental explorations (Michelini & Vercellati, 2012, 2014a, 2014b; Michelini & Viola, 2008).

In this context, we planned the educational path on EMI in the perspective of the Model of Educational Reconstruction (MER) (Duit et al., 2005). The path is described in the next sections after discussing international literature on EMI and after introducing both the research context and the methodology of data analysis. The discussion of results and the implications of this research are discussed at the end of this paper.

RESEARCH STUDIES ON LEARNING EMI

A wide literature in Physics Education about students' learning processes has been devoted to study EMI and has demonstrated that the involved concepts and models are particularly problematic for students (Bagno & Eylon, 1997; Duit et al., 1985; Maloney et al., 2001; Sanchez & Loverude, 2012; Secrest & Novodvorsky, 2005; Thong & Gunstone, 2008). The most common idea among students is that a current is induced in a coil only by the relative motion between magnet and coil. Therefore, most of students (at any school or university level) do not recognize that EMI can be observed also *(a)* when an electric circuit is warped in presence of a magnet (Maloney et al., 2001), *(b)* when it is rotated near a magnet (Maloney et al., 2001), *(c)* in the case of two coupled circuits without any kind of relative motion (Peters, 1984; Thong & Gunstone, 2008), or *(d)* that EMI is not observed if there is not flux variation, even in the cases of relative motions between magnet and coil (Maloney et al., 2001; Secrest & Novodvorsky, 2005; Zuza et al., 2014).

A deeper analysis of these difficulties shows that most of students has not a clear idea of magnetic flux, which usually is confused or identified with the concept of magnetic field (Saarelainen et al., 2007; Thong & Gunstone, 2008). In many cases students do not distinguish the concept of magnetic flux from its time variation and, consequently, most of them do not recognize the role played by the time variation of magnetic field flux (Ferguson-Hessler & de Jong, 1987; Kesonen et al., 2011; Sanchez & Loverude, 2012; Savelsbergh et al., 2002, 2011; Secrest & Novodvorsky, 2005).

Another crucial aspect related to EMI phenomena is represented by Lenz's law, which is fundamental for an in-depth comprehension of electromagnetic interactions, since it represents an expression of the energy conservation in such phenomena (Jones, 2003; Kesonen et al., 2011; Secrest & Novodvorsky, 2005). This aspect is frequently not clear for many students, because the idea that (the induced magnetic field that) "opposes the change of flux in time is interpreted as being in the opposite direction" of the inductor magnetic field (Bagno & Eylon, 1997).

Even if previous researches studied these learning difficulties through diagnostic tests (Ding et al., 2006; Maloney et al., 2001; Saglam & Millar, 2005) or written problem-solving activities (Bagno & Eylon, 1997; McDermott & Shaffer, 1998; Van Heuvelen et al., 1999), a research question is still open: which conceptual re-organization of electromagnetic phenomena can be planned to face the learning difficulties above described and to highlight the role of magnetic field flux and its time variation (Galili & Kaplan, 1997; Munley, 2004; Zuza et al., 2012, 2014; Zuza & Guisasola, 2013)? This crucial point represents the core of FNL law and conducts to additional and subsequent students' difficulties related to the formalization of EMI. In fact, some studies showed that students often reach partial knowledge of basic concepts of electromagnetic phenomena (field, flux, induction) and demonstrated that they are not able to associate the mathematical formalism (vector, integrals) to the physical descriptions of such key concepts (Albe et al., 2001; Savelsbergh et al., 2002).

Another crucial aspect about learning difficulties on FNL law emerges from a partial and local vision that students construct analyzing and interpreting the observed phenomena (Jelicic et al., 2017; Sanchez & Loverude, 2012; Savelsbergh et al., 2002). In fact, EMI can be approached facing separately and progressively each learning difficulty or proposing a global approach.

Within this debate, an important question is still open and has to be addressed: which is the best approach for students to overcome their local vision and to reach a global one? Some studies showed the advantages of a global approach, demonstrating that some students' difficulties regarding EMI arise from incoherent conceptualizations of magnetic field (and magnetic flux) and its representation through field lines (Bagno & Eylon, 1997; Duit et al., 1985; Guisasola et al., 2004): in many cases, students approach the concept of field lines as concrete objects or real entities, according to Faraday who "seemed to have attributed more reality to the field lines than we nowadays find acceptable" (Guisasola et al., 2004; Törnkvist et al., 1993). Such viewpoint affects the comprehension of EMI phenomena, because it can activate the idea according to which it is necessary a contact between field lines and coils to get EMI (Loftus, 1996; Michelini & Viola, 2009; Thong & Gunstone, 2008).

Various educational proposals have been planned and conducted to face the learning difficulties above described, as for example *(a)* the operative approach of the Leibniz Institute for Science and Mathematics Education (Härtel & IPN Group, 1986), *(b)* the Inquiry Based Learning (IBL) centered on experimental explorations (Abd-El-Khalick et al., 2004) and supported by tutorials (Heron et al., 2004; Mauk & Hingley, 2005; McDermott, 1991; McDermott & Shaffer, 1998) *(c)* the *Real Time Physics* approach (Sokoloff et al., 2007; Sokoloff & Laws, 2011). These different approaches have demonstrated that experimental activities play a crucial role also for a conceptual understanding of EMI phenomena. However, some critical aspects about FNL law remained still open, as for example *(i)* the significant role of relative motion (magnet-coil) in students' analysis of EMI, *(ii)* a coherent energetic interpretation of such phenomenon and *(iii)* a quantitative formalization of FNL law.

In this perspective, we planned an educational proposal based on an operative definition of magnetic field (in terms of field lines) with the aim of analyzing the contribution of such empirical approach in the conceptualization of magnetic field flux and, more generally, of FNL law. In our proposal, we planned two *Real-Time* quantitative experiments to face the crucial learning difficulty according to which the time-variation of magnetic field flux plays a crucial role in a typical EMI phenomenon. These two experiments were planned to study the time evolution of involved physics quantities: the first one offers students the opportunity to analyze the effects due to the rate of change of magnetic field flux; the second one makes it possible to control such time variations and to link them to the main important features of EMI. Our proposal integrates the IBL strategy (McDermott, 1991; McDermott & Shaffer, 1998) with the *Real-Time* approach (Sokoloff & Laws, 2011; Sokoloff et al., 2007), with the aim of involving students through *(a)* personal exploration of EMI, *(b)* identification of significant quantities (magnetic field flux and in particular its time variation) and *(c)* construction of the law that describes and interprets observed phenomenon (i.e., the law of FNL). In order to reach these last goals, we extended the use of *Real-Time* to activate the transition from the qualitative and phenomenological analysis to the formalization process.

We managed our didactic path with students by means of tutorials based on Prevision-Observation-Experiment (POE) cycle (Sokoloff et al., 2007; Theodorakakos et al., 2010), whose effectiveness is well known also in the domain of electromagnetism (Michelini & Viola, 2010; Sokoloff & Laws, 2011; White & Gunstone, 1992). In fact, taking into account that integrations of POE cycle in IBL and RTL strategies were explicitly implemented in different areas of physics (Hong et al., 2021; Hsiao et al., 2017; Ramnarain & Hlatswayo 2018), in our previous research experience such kind of integrations were effective to activate conceptual understanding about magnetism and EMI (Michelini 2006, 2010; Michelini & Vercellati, 2012, 2014b; Michelini & Viola, 2008, 2009, 2010).

THE PROPOSED PATH FOR EMI

Our proposal was designed according with the processes of the Design Based Research (Anderson & Shattuck, 2012; Collins et al., 2004; DBRC, 2003), within the theoretical framework of Model of Educational Reconstruction (Duit et al., 2005) in a vertical perspective (Constantinou, 2010; Méheut & Psillos, 2004; Michelini, 2010). Taking into account the learning difficulties about EMI above discussed and considering educational and disciplinary perspectives of various experiments about these phenomena (Fodor & Peppard, 2012; Ivanov, 2000; Kingman et al., 2002; Layton & Simon, 1998; MacLatchy et al., 1993; Ochoa et al., 1998; Roy et al., 2007; Sawicki, 2000; Trumper & Gelbman, 2000), we decided to introduce EMI *(i)* starting from a sequence of qualitative experimental explorations based on the IBL operative approach (Abd-El-Khalick et al., 2004; Heron et al., 2004; McDermott, 1991; McDermott & Shaffer, 1998) and then *(ii)* constructing quantitative basis for the comprehension of FNL law through *Real-Time* experiments (Bonanno et al., 2011; Priest & Wade, 1992; Ivanov, 2000; Kingman et al., 2002; Sokoloff et al., 2007; Huang et al., 2008; Fodor & Peppard, 2012; Michelini & Vercellati, 2014a). Our educational approach is based on an empirical introduction of the magnetic field concept, as a property of the space around a magnet (Michelini & Viola, 2008, 2009, 2010) and represented through the model of field lines (Michelini & Vercellati, 2012, 2014b). Such representation of magnetic fields is used as a conceptual tool to analyze real phenomena based on EMI (Michelini & Vercellati, 2012, 2014a). The core of our study is represented by a set of quantitative experiments planned to face the crucial learning difficulties related to the time variation of magnetic field flux. Our choice is based on the idea that *Real-Time* (hereafter RT) experiments offer students opportunities to analyze and understand phenomena in which the time variation of physics quantities (in this case the magnetic field flux) plays a crucial role (Sokoloff et al., 2007): in this perspective online sensors are used to follow in real time the observed phenomena and to construct a functional understanding (McDermott, 1991) of EMI and its mathematical expression represented by the FNL law.

The IBL strategy adopted in our approach was integrated with a problem-solving activity, in which students applied the conceptual understanding developed in previous step (i.e., the magnetic field and its representation) to construct both the concept of magnetic flux and the idea of its time variation (Guisasola et al., 2008; Michelini & Vercellati, 2014b). The quantitative experiments performed using online sensors offered students opportunities to analyze the central role of time variation of magnetic field flux in EMI phenomena (Bonanno et al., 2011; Michelini, 2006, 2018).

All the activities were conducted proposing students specific tutorials based on the POE cycle (Michelini & Viola, 2010; Theodorakakos et al., 2010; White & Gunstone, 1992). At the end of each session, students were stimulated to share their experimental findings, their individual conclusions and ideas and to give their final conclusions after classroom discussions. We did not introduce any concepts in a transmissive way: the sequence of experiments was planned according to the idea that the shared conclusions given by students at the end of each specific activity become the starting point for the subsequent exploration, so that the spontaneous elements shared after classroom discussions find meaning in the consecutive experimental practice. Consequently, these sequences of tasks allowed us to investigate students' ideas and to study their evolution during all the sessions.

RESEARCH QUESTIONS

Considering students' models of EMI discussed in literature (Albe et al., 2001; Bagno & Eylon, 1997; Ferguson-Hessler & de Jong, 1987; Härtel & IPN Group, 1986; Jelicic et al., 2017; Mauk & Hingley, 2005; Sanchez & Loverude, 2012; Thong & Gunstone, 2008; Trumper & Gelbman, 2000; Zuza et al., 2014), we planned this experimental path to study *(i)* how students analyze the main qualitative and quantitative features of EMI (in terms of magnetic field lines and flux) and *(ii)* which contributions RT systems give in the activation of students' learning processes when they analyze phenomena in which the time variation of the magnetic field flux plays a crucial role.

More explicitly, our challenge was to answer the following research questions:

RQ.1 How does magnetic field (and its flux) representation (in terms of field lines) affect the conceptualization of EMI?

RQ.2.1 How do RT explorations enhance the construction of interpretative models and formalization processes of EMI phenomena?

and in particular

RQ.2.2 How do quantitative RT experiments activate formalization of EMI?

Moreover, we aim to answer the following general research question concerning the impact of our experimental path on students' learning difficulties:

RQ.3 How does our approach contribute to overcome the conceptual knots on EMI discussed in the previous sections?

CONTEXT AND PHASES OF THE EXPERIMENTAL PATH

Research Context

We involved 10 classes of high school students (74 sixteen years-old and 72 eighteen years-old) in Calabria (a southern region of Italy), who never studied the magnetic field and its flux with their teachers before these experimental activities. Six of these ten classes were involved in a first preliminary study, planned and performed according with the design-based research (DBR) processes. This preliminary study was used to test the experimental setups, to validate the tutorials and to check the timing of the activities. Moreover, it showed us the need to stress two relevant parts in our sequence: *(a)* the operative definition of field lines (given by drawings) as a strategy to construct the concept of magnetic field and its formal representation; *(b)* the need to link both the graphical representations of magnetic field and the flux concept to the idea of field lines crossing a surface.

After this preliminary testing process, the revisited educational path (see Table 1, described in details in the next section) was proposed to 87 students of the remaining 4 classes (which represent the sample of the research here presented). Each class was enrolled in 5 sessions of 2 hours, involving students in hands-on explorations and *Real-Time* quantitative experiments, using tutorials as monitoring tools designed in the form of sequential stimuli questions.

The Experimental Learning Path on EMI

The activities proposed in this paper can be divided into the following three steps.

STEP-1. In the introductory IBL activities (Activities A, B, C, D - Table 1), students were involved in POE cycles (Theodorakakos et al., 2010; White & Gunstone, 1992) with the aim of constructing the concepts of magnetic field and of magnetic field lines, starting from the analysis of interactions between a magnet and other

Table 1. Activities proposed to students in our educational proposal

Session	Activity	Description	Hours
1	A.1 – A.2	Magnet as a source of magnetic field	1
	B.1 – B.2	Compass as a probe of magnetic field	1
2	C	Magnetic field lines	2
3	D	Magnetic field of current currying wire	2
4	E	Problem solving and POE cycle on EMI	2
5	F	Quantitative experiment on EMI by means of an electromagnetic Atwood's machine	2

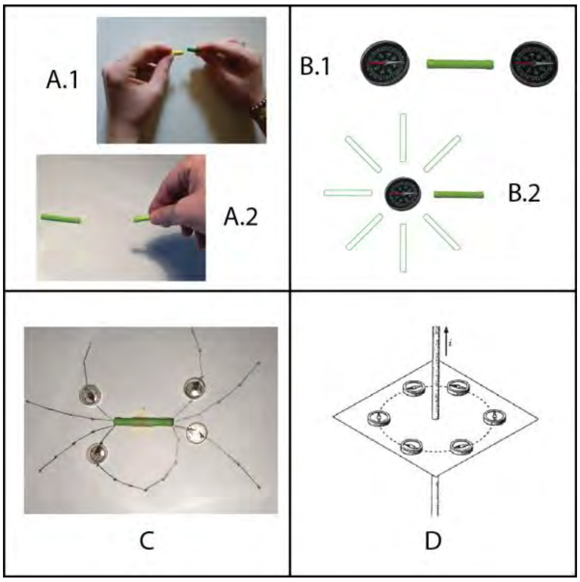


Figure 1. Step 1 activities: ***(A)*** interaction between two magnets held in hands (A.1) or between a magnet held in hand and another one on the desk (A.2); ***(B)*** exploration of the space around a magnet with a compass (B.1) and of the compass needle behavior while moving the magnet (B.2); ***(C)*** map of the space around a magnet; ***(D)*** and around an electric wire.

objects (different kinds of materials, magnets) in various configurations (Michelini & Viola, 2008, 2009, 2010) (see Figure 1 for some example).

The first exploration proposed interactions of a magnet with several objects (made by different materials) and with other magnets (A1 - two magnets held in hands; A2 - one magnet held in hand and the second one on the desk) (Bradamante et al., 2005; Michelini & Vercellati, 2012; Michelini & Viola, 2008). Then, they investigated the properties of the space around magnets using a low-cost compass as explorer (Activities B.1 and B.2) (Bradamante et al., 2005; Michelini & Vercellati, 2012; Michelini & Viola, 2008).

The second exploration allowed students to represent the magnetic field lines, mapping the space around a magnet following the orientations of compass needles (Michelini & Vercellati, 2012, 2014b) and drawing them in sequential positions (Activity C) (question Q1).

The main goal of this activity was to investigate if students could recognize a global structure and well-defined symmetries in their draws of field lines or if they could express a local vision by drawing segments without specific structures or connections. In order to reach this goal, students were asked to describe their draws (question Q2) and to share their descriptions and conclusions in the classroom discussion, concerning also their drawing in a three-dimensional (3D) perspective (question Q3).

The exploration of a simple Ørsted like experiment (Activity D) made students confident with the idea of an electric current as source of magnetic field (Michelini & Viola, 2008).

STEP-2. The activities proposed in the second step were planned with the aim of analyzing in which way students could use the empirical concept of magnetic field (in particular, its representation in terms of field lines, i.e., the outcomes of the first step) to analyze real phenomena based on EMI (Michelini & Vercellati, 2012, 2014a).

Students were asked to analyze EMI phenomena through a problem solving activity (see Michelini & Vercellati, 2014b). In activity E.1, they were challenged to produce a current in a wire using only a magnet, different wires and an ammeter (Figure 2), without

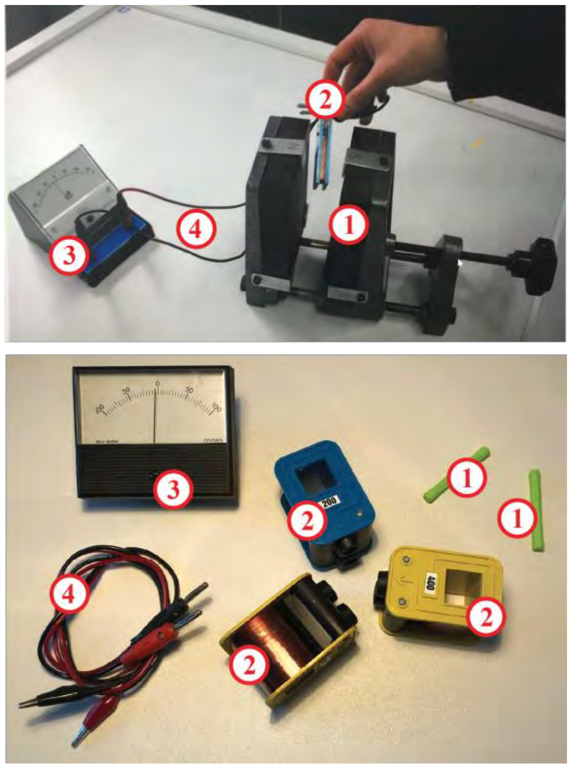


Figure 2. The materials used by students in problem solving activity (E1): magnets of different shape and magnetization ***(1)***, coils with different numbers of turns ***(2)***, microammeter with central scale ***(3)***, crocodile clip ***(4)***

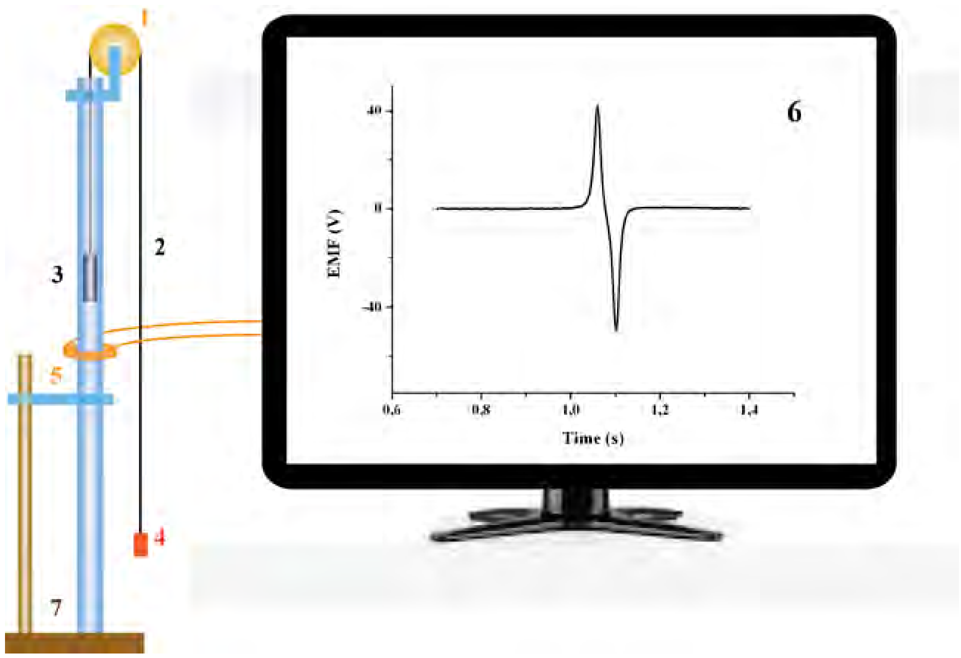


Figure 3. The electromagnetic Atwood's machine is composed by a pulley **(1)** and an inextensible string **(2),** through which a little magnet **(3)** is connected to a counterweight **(4)**. The magnet can cross a homemade coil **(5)** through a vertical Plexiglas tube. The induced EMF signal **(6)** is collected and analyzed through the *Visual Analyser* free software (Bonanno et al., 2011).

connecting a generator (i.e., a battery) (question Q4). They were asked, then, to investigate various experimental situations in which it was possible to obtain an induced electromotive force (EMF hereafter) following the tutorials (E.2): (1) introducing the magnet inside the coil, maintaining it at rest inside the coil and finally extracting the magnet from the coil (question Q5a); (2) introducing the coil inside two magnetic plates (question Q5b); (3) rotating the coil inside the two magnetic plates (Q5c); (4) putting the coil at rest close to a second coil connected to a current generator, in order to reproduce a time-dependent magnetic field (question Q5d). After these explorations, students were asked to describe through a single rule all the observed cases (question Q6).

STEP 3. The last step was planned as a sequence of *Real-Time* quantitative experiments (Hofstein & Lunetta, 2004; McNeil, 2004) and measures of EMI (Fodor & Peppard, 2012; Kingman et al., 2002; Sawicki, 2000; Sokoloff et al., 2007; Trumper & Gelbman, 2000) based on a low-cost and easy to use data acquisition system (Activity F).

We used an existing experimental setup (Bonanno et al., 2011) to perform quantitative measures of EMF induced by a magnet falling across a coil (see Figure 3). This Atwood's machine (hereafter electromagnetic Atwood's machine or EM Atwood's machine) allowed students to follow the magnet motion also when it was inside the coil. Moreover, it offered the opportunity to control/change the parameters affecting this motion and to correlate them to the induced EMF signal acquired through the *Visual Analyser* (a free software created at Tor Vergata University, and accessible online at: www.sillanumsoft.org/).

Students carried out three different experiments in small groups with the EM Atwood's machine (conducted through POE cycles), analyzing the features of the corresponding typical time-depending EMF: (RT1) prevision and description of the expected EMF graph in the case of magnet crossing the coil (question Q7a), followed by acquisition and analysis of the real graph; (RT2) prevision and description of the expected EMF graph changing respectively the starting heights and the counterweights (question Q7b), followed by acquisition and analysis of the real time graph. At the end of these experiments, each student produced individual conclusions about all the observed phenomena related to EMI (question Q8). In the final classroom discussion (in small and large group), students shared and compared their ideas with their peer and then all students expressed individually in written form their final conclusions about FNL law (question Q9).

MONITORING INSTRUMENTS AND METHODS

All the activities with students were conducted by means of tutorials consisting of stimulus questions based on IBL strategies (Abd-El-Khalick et al., 2004; Heron et al., 2004; Mauk & Hingley, 2005; McDermott, 1991; McDermott & Shaffer, 1998) within sequences of POE cycles (Sokoloff et al., 2007; Theodorakakos et al., 2010). The previous section summarizes the key steps, the questions and the specific requests of the tutorials, through which we analyzed in details students' answers. These tutorials had the dual role of engaging students in a challenging inquiry learning environment and monitoring their learning paths.

The tutorials were filled always individually by each student, even in the activities conducted in groups. In particular, students performed individually all the previsions on the experiments as well as the synthesis of the experimental results. Therefore, our analysis of data provides an overview of the individual predictions made by each student regarding the different experiments as well as the learning outcomes for each activity (i.e., individual reflections after group analysis about observations and experimental results). Students' conclusions about a group of experiments, always expressed individually, were collected in two different times: in a first step (called in the rest of data analysis "before group discussion") students' answers, given after small groups interaction and discussion, represent an individual re-elaboration of the interactions/comparisons with few classmates (2-3); in a second step (called in the rest of data analysis "after group discussion") students' answers represent an individual synthesis made by each student after a collective discussion in a large group (class group).

We performed the qualitative data analysis of students' open answers given for each question of our tutorials, classifying different categories of answers that put in evidence interpretative models and conceptual referents (Denzin & Lincoln, 2011; Erickson, 2012). For each specific investigated phenomenon/aspect we defined the elements expected a priori (Niedderer, 1989) taking into account:

- the conceptual elements highlighted by the re-organization of EMI in the perspective of the MER, answering in this way to the question "*which are the basic concepts?*";
- the learning difficulties highlighted by literature (discussed in the previous section).

After this preliminary step, we analyzed students' answers focusing on the proposed conceptual models: we identified these models studying the key words/verbs proposed by students and we used such models to classify all their answers (i.e., all their written sentences) (Miles et al., 2014). The categories were then refined with examples of sentences and/or images taken from students' answers (Bradley et al., 2007; Glaser & Strauss 1967; Miles et al., 2014). Such classification was performed through a sharing process of ideas among all the researchers involved in this study.

Almost all the categories obtained from the qualitative analysis are exclusive, only in few cases (highlighted in the following analysis) we introduce non-exclusive categories. This aspect made it possible to study also the distribution of categories, the correlations between them and the related interpretative models.

Several studies have demonstrated that graphical representations are important conceptual referents to link significant physics quantities to the observed phenomena and to understand their time evolution (Pospiech et al., 2019; Testa et al., 2002). Consequently, graphs represent significant tools for the analysis of the students' conceptual models (Fan, 2015; Scaife & Heckler, 2007; Stefanel, 2019; Windschitl et al., 2008; Woolnough, 2000). These results highlighted by international literature led us to give particular attention to the analysis of students' graphical representations proposed during all the activities. In particular, we analyzed the connections proposed by students between graphs and phenomena, between the iconic features of the sketched graphs, the quantities represented, and the specific processes involved in the explored phenomena.

In the follow, we synthetize the qualitative criteria of our analysis for the different questions Q1-Q9.

(Q1-Q2-Q3) <u>Representation and description of the compass needle orientation in sequential positions</u>. According with Scaife and Heckler (2007), the representation models of magnetic field affect significantly the approach to different concepts of magnetic phenomena. Consequently, the main goal of this section was *(a)* to analyze the introductions of the magnetic field concept given empirically by students (through the operative definition of field lines) and *(b)* to compare such ideas, at the end of the sequence, with the results of the qualitative and quantitative experiments on EMI, in order to demonstrate and identify specific links and patterns.

The criteria of data analysis were defined considering the main characteristics of magnetic field lines: (1) nature of the field, entangled global structure in the space around a magnet; (2) axial symmetry related to the axis of magnet and planar symmetry with respect to the medial plane of magnet; (3) representations with continuous smooth lines without intersection (also inside the magnet), whose normalized flow (i.e. the number of lines per unit of surface) is proportional to the intensity of the field (Ding et al., 2006; Galili, 2001; Guisasola et al. 2004, 2008; Härtel & IPN Group, 1986; Kesonen et al., 2011; Maloney et al., 2001; Scaife & Heckler 2007). We focused only on the following characteristics of the graphs and of the related descriptions, that could be activated by the preliminary exploration of the magnetic field with the compass:

(1) continuity vs discontinuity: drawings representing disconnected segments without any global or local structure put in evidence a point-by-point representation of compass-needles without any guiding model; drawings formed by continuous broken lines showed a qualitative idea of field lines or (more generally) of some structure that can be explored through a compass (Bradamante et al., 2005; Bradamante & Viennot, 2007).

(2) local vs global structures: drawings focused on local structures emphasized the role of magnetic poles and of the space around it; drawings with

global structures (i.e., north-south pole or axial symmetries) highlighted symmetries of the magnetic field in the space around the magnet.

(Q4 - Q5 - Q6) Induction of currents in a coil without a battery. Studies about EMI highlighted the importance of introducing the concept of magnetic flux and its time variation (Galili et al., 2006; Guisasola et al., 2004; Jelic et al., 2017; Maloney et al., 2001) as well as the possible connection between field line representations and the role of magnetic flux (Bagno & Eylon, 1997). Therefore, we chose to analyze learners' explanations focusing on:

(Q4) the causes/effects of EMI and the inversion of induced signal, distinguishing simple descriptions of observed phenomena from introductions of physics concepts/models;

(Q5a) the representations of field lines (if and eventually how) used to describe EMI phenomena;

(Q5b) the concept of flux (if and eventually how) introduced and its time variation;

(Q6) the concepts used by students to summarize the results obtained at the end of the exploration (of field lines). In which way did they introduce the representation in terms of field lines? How did they use the concept of flux variation of magnetic field (even in terms of field lines crossing the coils) in events based on EMI? Which were the interpretative aspects of FNL law introduced by students?

(Q7) Expected graphs of the EMF induced in a coil by a magnet falling inside (in different configurations, i.e., RT1 and RT2). The research about the concept of induced current and in particular about the role of FNL (Albe et al., 2001; Bagno & Eylon, 1997; Galili et al., 2006; Savelsberg et al., 2002; Secrest & Novodvorsky, 2005; Tong & Gunstone, 2008; Zuza et al., 2012) led us to focus our attention on the role of flux and its time variation (more general, on the role of time in the process), as well as on the relationship between the process of EMI and its effect. The graphs and the related descriptions were grouped considering the following main features: i) number of peaks; ii) shape (amplitude, width, sign) of peaks; iii) symmetries/asymmetries of the graphs.

This analysis made it possible to investigate *(a)* if students could focus on the effects of magnet approaching the coil or leaving the coil (corresponding to two-peaks with different signs), *(b)* if they could identify the role of time in the accelerated motion of the magnets (highlighted by the asymmetry of the two peaks), *(c)* if they could describe the graphs in terms of magnets movement (towards the coil or away from the coil) or if they could associate the graph to the magnetic field (and consequently to the position of the magnet within the coil).

(Q8 - Q9) The literature about representations in physics (Fan 2015; Testa et al. 2002; Windschtl et al. 2008) have claimed that the iconic elements of graphical representations offer the opportunity to construct important connection between the analyzed process and physics quantities described through such representations. Moreover, graphical representations often underlie specific conceptual models related to the observed phenomenon (Albe et al., 2001; Pospiech et al., 2019; Windschtl et al. 2008; Woolnough 2000). In the present research, we analyzed students' descriptions of the proposed graphs distinguishing the following typologies:

i) description of the graph in terms of changes (increasing, decreasing), of stationary phases and of other features (positive sign, inversion of the sign), without connection to the represented quantities or to the phenomenon;
ii) description of the different parts of the graph and connection with the different phases of magnet motion;
iii) introduction of physics quantities to describe the observed phenomenon (i.e., the conceptual references).

For data analysis, we defined a-posteriori categories, starting from these three typologies of descriptions.

DISCUSSION OF DATA AND RESULTS

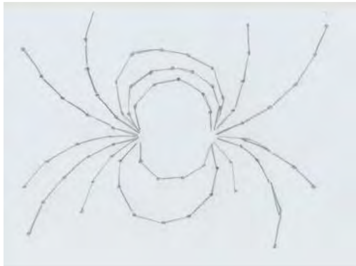
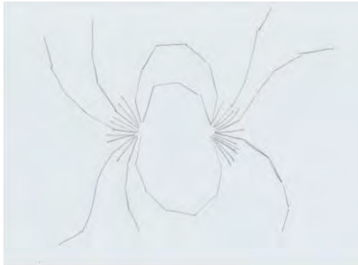
In this section we report the analysis of data concerning 87 students of four classes, focusing on: *(a)* students' representations of compass-needles in the space around a magnet (magnetic field lines), *(b)* qualitative explorations of different situations in which an EMF is induced in a circuit; *(c) Real-Time* quantitative experiments (RT1 and RT2) performed by means of the electromagnetic Atwood's machine; *(d)* individual conclusions given at the end of the sequence and after the last classroom discussion.

Representation of the Compass Orientations Around a Magnet (Magnetic Field Lines)

As before described, after the exploration of magnetic interactions, students were asked to draw individually the orientation of compass-needles in the space around the magnet and to describe their drawings (Q1-Q2-Q3). The analysis both of drawings and of descriptions was performed according to the elements defined a priori in the "*Monitoring instruments and methods*" section (i.e., continuity vs discontinuity and local vs global structure). We defined four categories of graphical representations (from GR1 to GR4, see Table 2), whose distribution is showed in Figure 4.

The first two categories (GR1 and GR2) (58%) show that students constructed an image of continuous lines, in which emerge some evident structures and symmetries: global and general for the more frequent category GR1 (44%), local and partial in the case of the category GR2 (14%). This last category had been

Table 2. Classification of graphical representations drawn by students

Category GR1 *Global configuration and symmetry*	The pen strokes outline continuous (in many cases broken) lines highlighting a global structure (behavior) and symmetry (Figure 4A)	
Category GR2 *Global structures*	The pen strokes outline continuous broken lines, mainly focused on the behavior of the compass-needle around the magnetic poles and characterized by a north-south symmetry, without axial symmetries (Figure 4B)	
Category GR3 *Broken lines*	The connected pen strokes form broken lines without structure, symmetry, global or local configuration (Figure 4C)	
Category GR4 *Single unconnected segments*	The pen strokes are not connected and represent point by point a local orientation of the compass-needle (Figure 4D).	

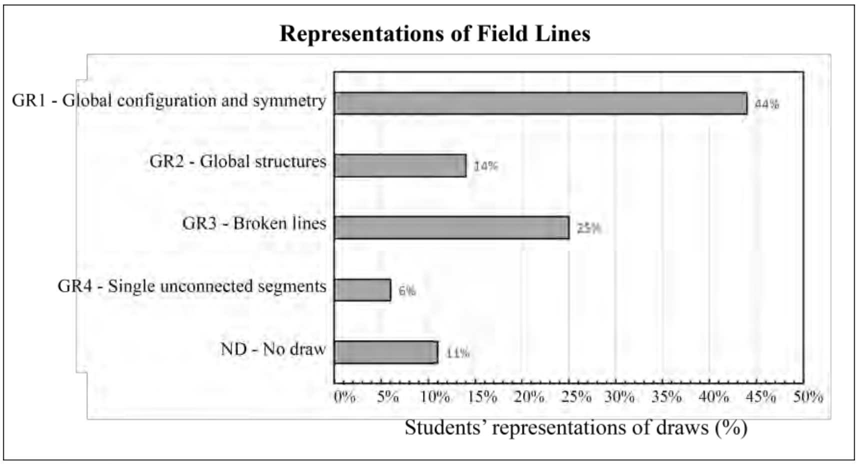


Figure 4. Representations of field lines (for 87 drawings): *(GR1)* global configurations and symmetries; *(GR2)* global structures; *(GR3)* broken lines without symmetry or global configuration; *(GR4)* sequence of segments without connections between them

identified also in previous studies conducted with 8-11 years old pupils, according to which pupils had identified their graphical representations as a simple "picture" of what they had observed during the exploration (Bradamante et al., 2005; Bradamante & Viennot, 2007).

The categories GR3 and GR4 (31%), characterized by "no structure" or "no symmetry", show that students

Table 3. Classification of students' descriptions of their drawings

Category	Ecample
D1: Description highlighting a global symmetry (11% of students)	*All the lines represent a behavior from a pole to the other one; it is possible to observe a symmetry with respect to the magnet axis* (i.e., up and down symmetry) *and to center of the magnet* (i.e., left-right symmetry).
D2: Detailed descriptions around the poles with global symmetry (23% of students)	*Close to the magnet, the lines converge on the poles, while moving away from the magnet the lines show different closed and symmetric circular paths.*
D3: Detailed descriptions around the poles with partial symmetry (2% of students)	*The line of the magnetic field that we represented seem to be directed from a magnetic pole to the other one, with the same shape on both the poles* (i.e., left-right symmetry).
D4: Detailed description focused on the behavior of the compass-needle around poles (43% of students)	*All the lines that represent the behavior of the compass converge on the magnet poles. We can observe that moving the compass close to the first pole and then to the other, the needle shows a different behavior.*
D5: Generic description without highlighting any structure and without focusing on the role of the magnetic poles (3% of students)	*We observe many orientations of the lines.*
(ND) No Description (18% of students)	

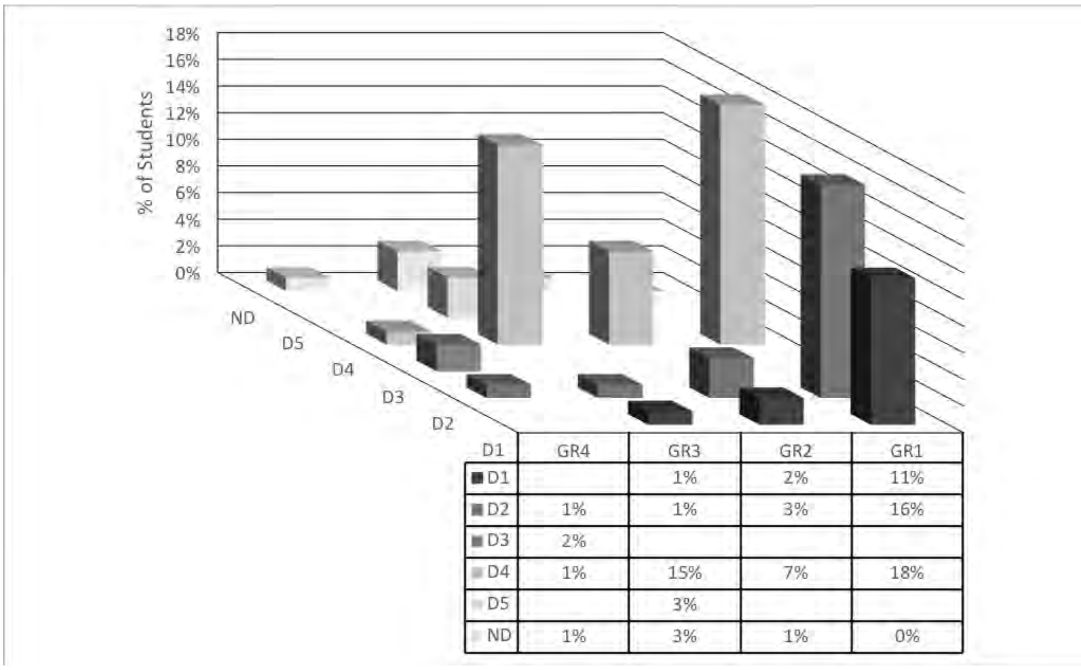


Figure 5. Distribution of the categories introduced to classify the graphical representations (see Figure 4) with respect to the corresponding descriptions given by students (defined in Table 3)

performed their task without recognizing a structure from their own draws.

We used the same relevant aspects proposed for graphical representations to construct five categories of analysis related to students' descriptions of such representations (see Table 3), according to the ideas of local and global symmetries, as well as to the role of magnetic poles (emphasized as relevant aspect in the categories defined a posteriori).

Considering both the classification of field lines representations (see Figure 4) and the related descriptions (defined in Table 3), we constructed mutually exclusive categories and the related frequencies distribution (see Figure 5). Figure 5 shows that the local vision focused on the role of the magnetic poles emerges from students' descriptions (80% in the categories D2, D3, D4 and also a D1) more than from their graphical representations (58% in the categories GR2 and GR3). An almost specular result regards the global vision of the magnetic field, since students' attention toward a global structure of symmetry can be identified in more than half of graphical representations (58% in the categories GR1 and GR2) even if in many cases it was not described by students. Only 33% of students proposed symmetries both in their draws and in their descriptions (i.e., intersection between GR1 + GR2 and D1 + D2 categories). These students played a crucial role in the classroom discussion at the end of this section, because they helped most of their classmates to overcome the local vision proposed in the first answers

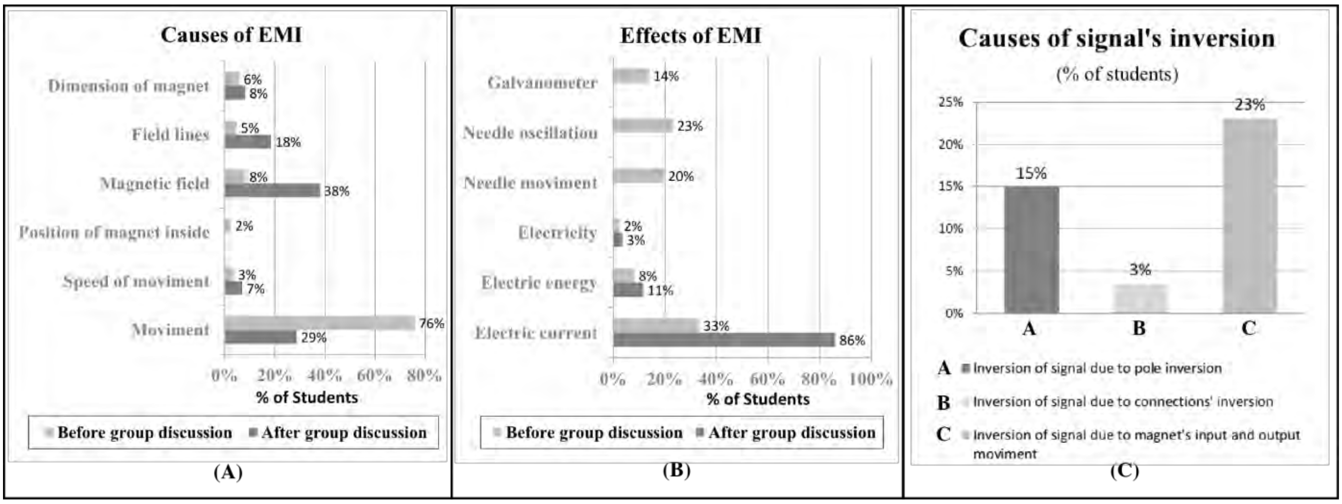


Figure 6. Students' answers to question (Q4) classified considering (A) the causes, (B) the effects and (C) the causes of the signal inversion (87 students). These three graphs represent non-exclusive categories. Graph (A) and (B) compare students' individual conclusions respectively before (light-grey columns) and after (dark-grey columns) group discussion; Graph (C) shows the causes of signal inversions identified only by 41% of learners after group discussion

and to move their ideas towards a global symmetry in which the magnetic poles play a crucial role. As a consequence of this interactive process among peers, when explicitly required (Q3), almost all students affirmed that their drawings represent just a part of a 3D symmetrical structure ("*the lines are symmetric in the 3D-space, because they are independent from the used drawing plane*").

Problem Solving Activity on Explorations on How to Produce EMF Without a Battery

In this section we discuss the outcomes of the problem-solving activity (Michelini & Vercellati, 2012) in which students were asked to answer the question "how is it possible to produce an electric current in a coil, without using a battery?" (Experiment E1, Question Q4). The sentences written individually by each student were collected after the small group activities.

In addition to the elements described a priori in the methodology section (see question Q4), we added a posteriori the following aspects: *A)* the dimension of magnet and its position with respect to the coil (as regards the causes of EMI); *B)* "*oscillations of galvanometer*", "*oscillations of compass needle*", that can be related to the field intensity (as regards the effects of EMI); *C)* the "*movement of compass needle*", which is only a qualitative indicator of the phenomenon (as regards the effects of EMI); *D)* the inversion of magnet poles and/or of the battery polarity (as regards the causes of signal inversion).

Figure 6 summarizes the answers of all the involved students (87 students). The categories are non-exclusive and were classified considering *(A)* the causes and *(B)* the effects of EMI described by students before (light-grey columns) and after (dark-grey columns) the classroom discussion.

Before classroom discussion (Figure 6a, light-grey columns), all students identified at least a way of generating an electric current in a coil (by employing a magnet). We divided the causes (of the induced current) proposed by students in two group of categories: *(i)* the first one related to something that moves and *(ii)* the second one to the role of magnet, magnet-field or field-lines. Confirming the main results of international literature (Albe et al., 2001; Bagno & Eylon, 1997; Härtel & IPN Group, 1986; Jelicic et al., 2017; Loftus, 1996; Maloney et al., 2001; Saarelainen et al., 2007; Secrest & Novodvorsky, 2005), students linked more frequently EMI phenomena to the motion of magnets (i.e. the first group which gathers the categories *Movement* and *Speed of Movement*):"*magnet approaches the coil*", "*magnet enters the coil*" and "*magnet exits from the coil*" (76%), In some cases, students proposed the idea of "*magnet-coil relative motion*" or put in evidence the role of "*magnet speed*" (3%). This last category was differentiated from *magnet movement category* because it introduces the idea that time plays an important role in the physics process. The second relevant group of categories (21%) focus on the role of the magnet in this phenomenon. It includes four different categories: two of them regard magnet position or its dimension (i.e., categories *Dimension of magnet* and *Position of magnet inside*), two of them refer generically to magnetic field (category *Magnetic Field*) or to field lines (category *Field Lines*).

The EMI effects were described as "*electric current*", "*electricity*" and "*electric energy*" in the coil or through other observed phenomena as "*needle movement*", "*needle oscillation*", "*galvanometer signal*" (Figure 6b, light-grey columns). After group discussion, a large part of students (41%) spontaneously recognized also that it was possible to obtain a "*sign inversion*" of EMF, "*due to pole inversion*" (magnet), "*due to the inversion of connections*" or "*due to magnet entry and exit*" (Figure 6c).

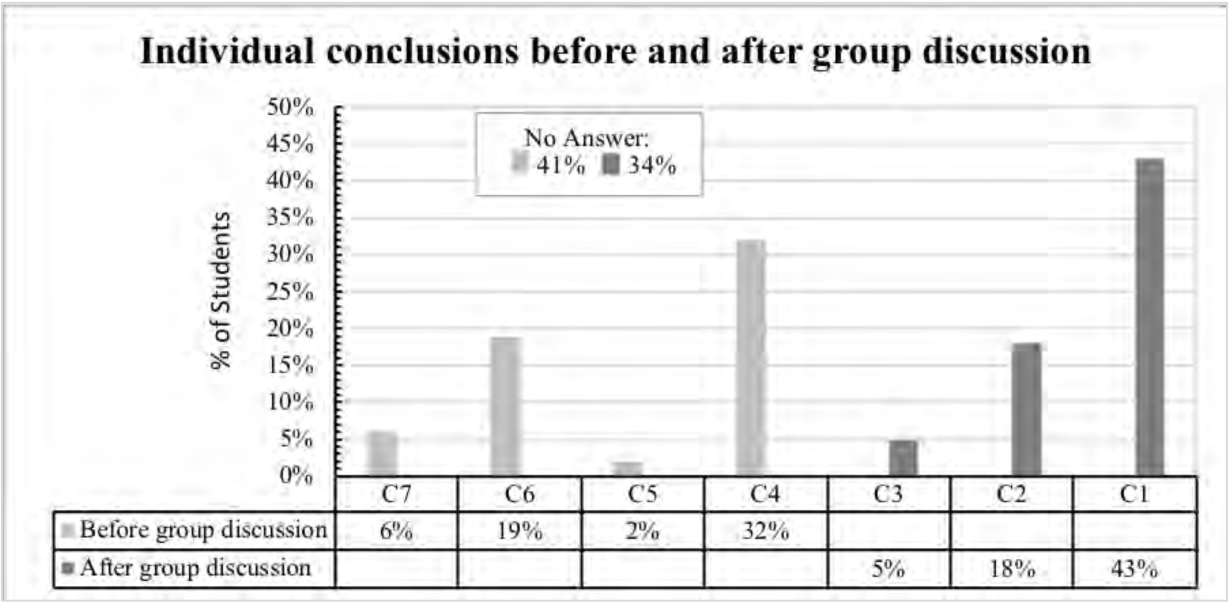


Figure 7. The distribution of causes of EMI according to students, before (51 students) and after (57 students) group discussion, are fully disjoint (see Table 4 for the definition of the categories)

During the classroom discussion, students shared their ideas and discussed the conclusions reached by each small group. After classroom discussion (Figure 6a, dark-grey column), only 1/3 of students proposed again the idea that magnet movement or magnet speed are the causes of EMI ("*magnet movement*" 29% and "*magnet speed*" 7%). In fact, more than half of students focused their attention on the role of magnetic field (38%) or of field lines (18%), which induced an electric current in the coil (Figure 6b, dark-grey column).

POE Cycle on EMI.

After the problem-solving activity, students were stimulated through a POE cycle to explore experimentally all the situations in which it was possible to induce an EMF inside a coil (Q5a-d). As we said before, even if problem solving activities were conducted in small groups, students proposed their individual reflections after the small group discussions and analyses.

In the individual conclusions before group discussions, 59% of students (51 of the 87 involved students) explained their ideas regarding the causes of induced EMF in terms of relative motion between coils and magnets or highlighting the generic role of magnetic field or field lines (Figure 7, light gray). The remaining 41% of students did not report their individual conclusion. Group discussion activated a generalized change documented by the different distributions of answers (Figure 7, dark gray). After the group discussion (Q6) we collected students' ideas regarding the causes of EMI that took advantages of the collective discussion in the activation of learning processes. The prevalent causes of EMI (for the 66% of students, i.e., for 57 over the 87) were "*field line variation, and then magnetic field flux variation*" (28%) or simply "*magnetic field flux variation*" (66%). (Figure 7, dark gray). Considering that we had never introduced such concepts in our discussions with students, we tried to investigate, at the end of this activities, the reason of such important improvement asking directly to students and some of them answered that "*after the problem solving, I made spontaneously a research and I found online something about the role of magnetic flux in the EMI*". This concept was introduced by an important number of students only after group discussions, highlighting the role of the peer interactions in the educational process: after comparison between peers the knowledge of some students became a classroom heritage. The remaining 34% of students did not answer also after the group discussion. Table 4 summarizes all the categories obtained from the qualitative analysis of students' conclusions before and after the group discussion.

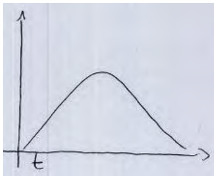
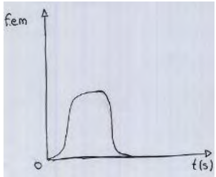
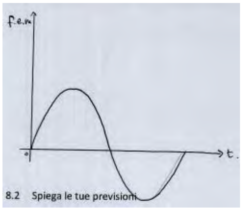
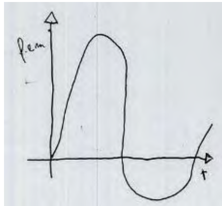
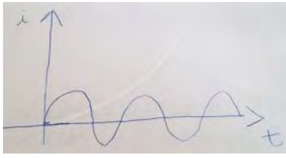
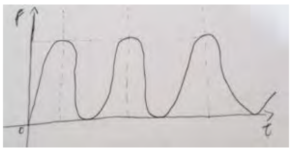
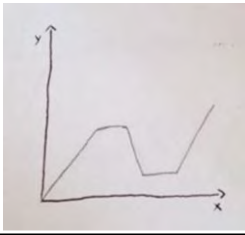
The evolution of students' ideas (compared with the results described previously in Figure 6) represents a significant result arising from the progression of tasks given to students (planned in each tutorial): experimental exploration performed in small group, followed by an individual re-elaboration and then by a classroom discussion.

The shift of students' answers, illustrated in Figure 7, shows the role of our educational sequence in the activation of a coherent vision on EMI, never faced by students before these activities (as specified before). Despite this important result, there is a not negligible number of "*no answer*" (41% of the total sample before and 34% after the group discussion) that highlights the persistence of difficulties as regards EMI for 1/3 of students.

Table 4. Causes of EMI described by students before and after group discussion

Category	Example
C1: Variation of magnetic flux or variation of flux of field lines	*EMI is caused by a variation of the flux of the magnetic field lines*
C2: Voltage difference generated by kinetic energy of magnet	*The movement of the magnetic field generates a kinetic energy that produces a potential difference*
C3: Electric field generated by magnetic force	*We observed that the electric field was generated by the magnetic force*
C4: Role of field lines - magnetic field	*The magnetic field produces an electric current and consequently an electric field.*
C5: Interaction between quantities	*In this process various physics quantities are involved: speed of magnet, electric current, field lines.*
C6: Interaction or relative motion between objects	*EMI is caused by relative motion between the magnet and the coils.*
C7: Other answers	*The explorations performed by us depend on the force*

Table 5. Classification of 87 students' predictions of the expected signals (ES)

Category	Description	Examples of Graph
ES1 (48%): Graphs with only a positive peak; half of them proposed a peak characterized by a stationary state (see the second figure).	*The graph increases when magnet approaches to the coil, it is constant when magnet is inside the coil and it decreases when magnet leaves the coil.*	 
ES2 (27%): Representations in which a positive peak and a negative peak were distinguished.	*We obtain maximum peaks when magnet enters and leaves the coil.* *The electric current increases when magnet approaches to the coil, it decreases until zero when magnet is inside the coil and then a negative peak appears.*	 
ES3 (20%): Predictions of periodic graphs, where the presence/absence of change in sign do not affects significantly the descriptions.	*positive and negative peaks.* *maximum and minimum peaks.*	 
ES4 (5%): Two peaks with a growing trend.	*The EMF increases when magnet approaches to the coil and it increases again when magnet leaves the coil.*	

Real-Time Quantitative Experiments – The Magnet Falling Inside the Coil

The first quantitative experiment (RTL1) familiarized students with the typical EMF signal induced when a magnet (connected to a counterweight through an EM Atwood's machine) falls through a coil. Students were asked to represent the graph of the expected signal and to describe the proposed graph (question Q7a). The data here presented regards the individual analysis/re-elaboration proposed by students before the classroom discussion. According to the criteria of analysis presented in the "*Monitoring instruments and methods*" section, the graphs were grouped considering their main features and the meaning of such features classified by students' descriptions. The qualitative analysis made it possible to classify the expected graphs (i.e., the Expected Signal) proposed by students in four categories (Table 5) related to questions Q7 and Q8, described in the subsection of the experimental learning path on EMI (we added a posteriori also the categories ES3 and ES4).

The graphs of ES1 category are based on the idea that the induced signal is related to the intensity of magnetic field (or of its flux), rather than to its variation. This is

Table 6. Qualitative Analysis of students' description according to physics quantities/concepts used by students in the descriptions of their graphs (mutual exclusive categories)

Category name	Operative description of category
No Physics quantities (20%)	*The starting point of the graph is zero; it increases until the maximum value, it remains constant and then it decreases again towards the initial zero value.*
EMF (32%)	*The electromotive force increases when the magnet enters the coil and decreases when it leaves the coil.*
Current (24%)	*When the magnet crosses the coil, we observe a passage of electric current.*
Variation of force (13%)	*When the magnet moves up and down in the coil, it experiences a variation of forces.* *The graph is generated by a variation of force, that is maximum when the magnet cross the coil and it is minimum when magnet is far from the coil.*
Field lines (11%)	*The field lines are at the maximum value when they move close to the magnet, while they decrease when it moves away from the magnet.*

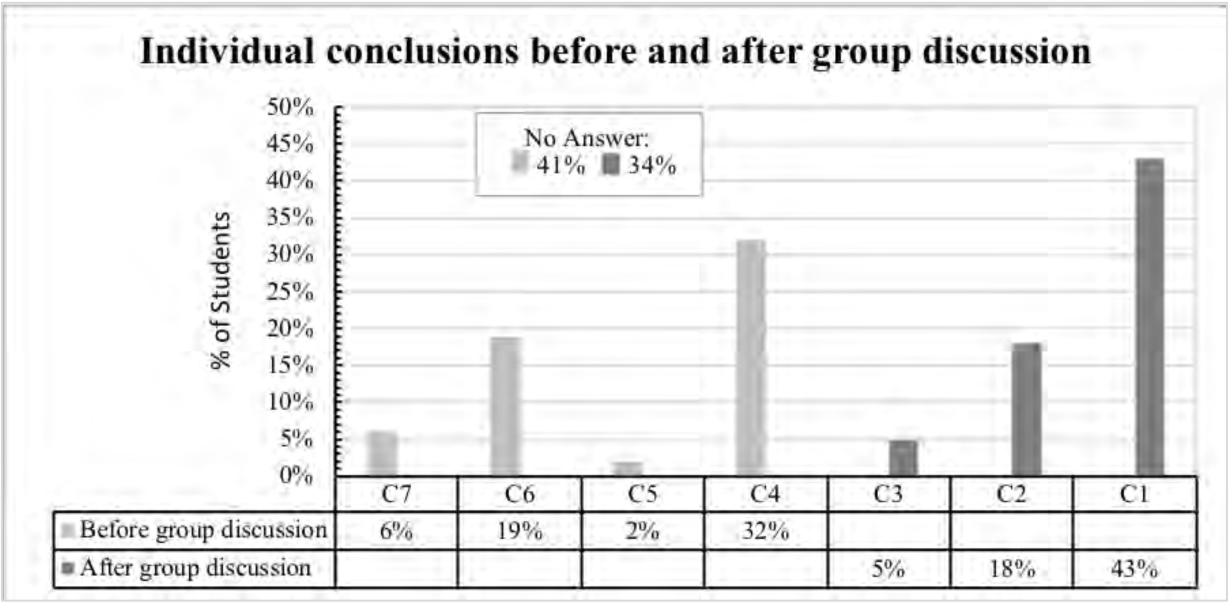


Figure 8. Distribution of the physics quantities or concepts introduced in students' descriptions of the expected graphs classified in Table 5 and Table 6

particular evident in the graphs with a stationary phase (see the second graph of ES1 in Table 5).

As regards the category ES2, we did not differentiate the equal amplitudes (symmetry observed in 2/3 of cases) by the different amplitudes of the peaks (asymmetry observed in 1/3 of cases). In fact, the predictive graphs with different positive and negative amplitudes seemed to be casually introduced, for this reason they were grouped in the same category. These graphs are based on the opposite point of view of the ES1, since they put in evidence that there is an inversion of sign when the magnet enters/leaves the coil. This is an interesting results due to the experimental explorations performed in the previous steps of our sequence, which allowed students to deal with the important learning difficulties related to the Lenz's law (Bagno & Eylon, 1997; Jelicic et al., 2017; Jones, 2003; Loftus, 1996).

As regards the category ES3, students explained in informal interviews a posteriori that they predicted an oscillating graph because they had thought about oscillating magnets inside/outside coils. Finally, the category ES4 introduces the idea of a different slope in the two phases of magnet's motion (while entering or leaving the coil), representing an increasing signal due to an accelerated motion of the magnet (as explained by the interviews made a posteriori).

Table 6 summarizes the physics quantities or concepts introduced by students to explain or justify their graphs. More than 80% of students introduced some physics as conceptual reference in the descriptions of their graphs: *(a)* the induced EMF (33%); *(b)* the induced electric current (25%); *(c)* the forces acting during the transition of the magnet through the coil (13%); *(d)* the magnetic field on the coil (11%). The 16% of answers described only the motion of magnet: "*The magnet (at the beginning) falls quickly, it slows down crossing the coil and then it falls again quickly*". The 20% of students did not introduce any physics concepts to describe their graphs.

Figure 8 shows the distribution of the physics quantities/concepts classified in Table 6 with respect to the expected graphs classified in Table 5.

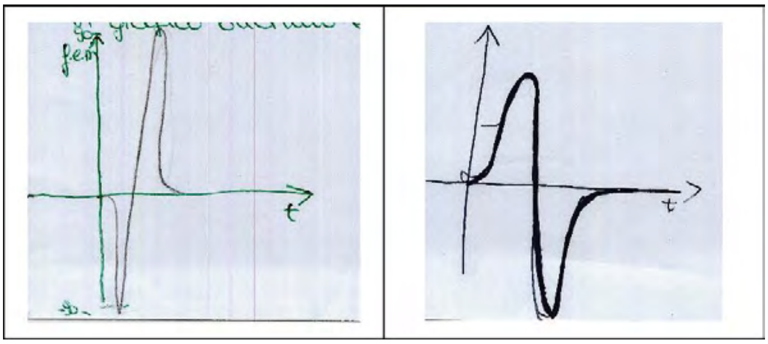


Figure 9. Two examples of graphs obtained by students after EM Atwood's machine experiment, which put in evidence (graphically) the differences between the absolute values of peaks amplitude

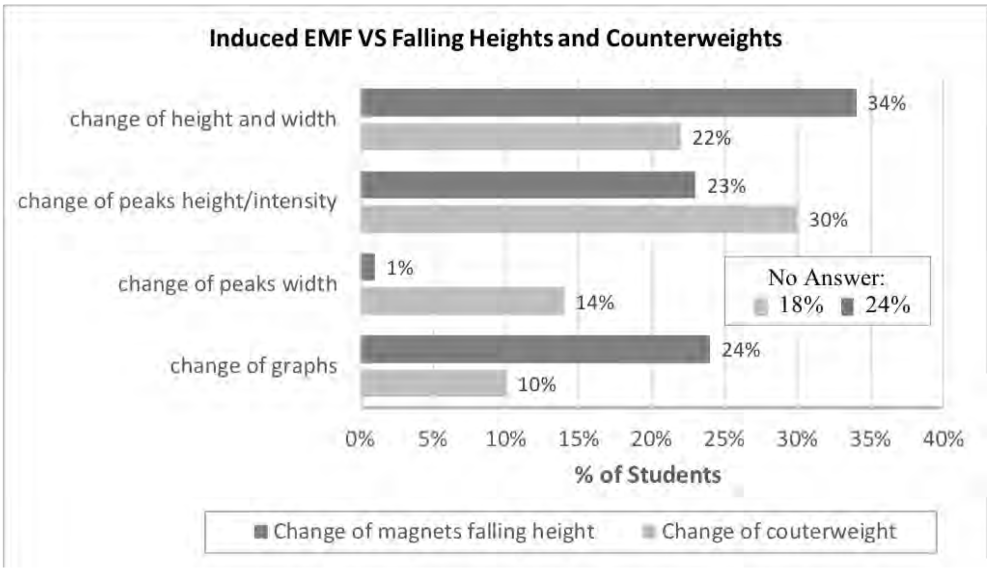


Figure 10. Students' prediction about the relationship between induced EMF and *(a)* the magnets falling heights (82% of students answered to this question) *(b)* the counterweight (76% of students answered to this question)

The experiment performed by students and the comparison with their predictions changed their ideas about the typical EMF signal obtained by means of the EM Atwood's machine. In this step, more than two-third of learners (70%) remarked their wrong predictions while 22% of them answered that "*the experimental results confirmed the prediction previously proposed*". In the first group of learners (stressing the differences between prevision and observation) many of them highlighted the difference between the one-peak predicted graph and the two-peaks graph observed experimentally (we named this difference as a **first-order difference**). Also, some student who predicted two-peaks graph (about 39%) put in evidence some minor differences between predictions and observed results, as for example the asymmetry between the two peaks or the maximum amplitudes (we named this kind of as a **second-order difference**).

It is interesting to observe that only the students that put in evidence first-order differences introduced in this step interpretative elements in their comments: "*Our hypotheses were wrong, we predicted only one peak. Moreover, the second peak is higher than the first, because the magnet velocity is bigger*" (7%), "*the motion is accelerated*" (5%), "*My graph is wrong, because I predicted only one peak. The second peak is higher than the first, because there is a larger number of field lines when the magnet leaves the coil*" (6%).

While comparing individually their predictions with experimental results, most of students (70%) reproduced the obtained experimental graphs even if it was not requested (Figure 9 shows two typical examples of these graphs). These examples stress the role of time and the asymmetry of the two peaks: the first kind of graph emphasizes only the different amplitude of peaks, the second one seems more focused on the invariance of the areas delimited by these two peaks.

Real-Time Quantitative Experiments - The Effects of Changes in the Atwood's Parameters on the EMF

Concerning the role of changes in the EM Atwood's machine parameters (question Q7b), students analyzed the relationship between the induced EMF and *(a)* the falling height or *(b)* the counterweight (Figure 10). In this phase a not negligible number of students avoid to answer to these questions: 82% of them proposed a prevision about the relationship *EMF vs falling height*, 76% proposed a prevision about the relationship *EMF vs*

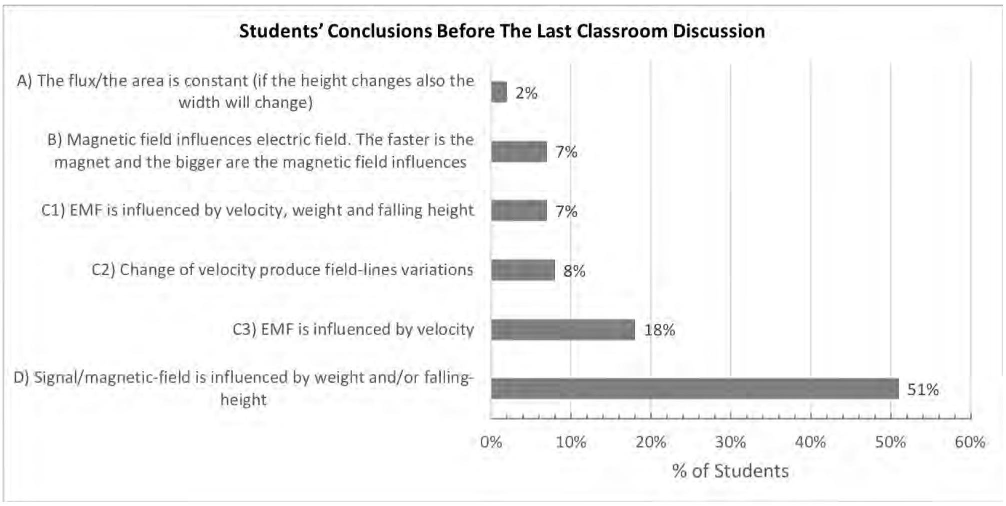


Figure 11. Students' conclusions before the last classroom discussion

counterweight. Among them, while 1/3 of students predicted a generic change in the graph, most of them (70-76%) predicted that the amplitude (called by students' height) and/or the width of the EMF signal change according to the magnet falling heights and to the counterweight, specifying that "*If the falling height increases the width of the peak decreases*" or "*if we increase the counterweight, the height of the peak decreases and the width increases*".

After performing the RTL2 (i.e., in the comparative phase of the POE cycle) all the 87 students described the observed graphs, and most of them confirmed that "*the prevision is correct*" (respectively 62% as regards the relation *EMF vs Falling Heights* and 79% as regards the relation *EMF vs Counterweight*), stressing descriptive aspect of the process, as for example "*changes of magnet speed*" or "*changes of height and width*". Only in few cases (5%) they included interpretative aspects: "*the EMF measured using the counterweight is smaller than the EMF obtained without the counterweight*".

The two RTL experiments familiarized students with the typical EMF signal obtained with the EM Atwood's machine, so that some of them avoided to make the predictions of the RTL2 because "*of course the graph changes while changing the falling height or the counterweight*". Moreover, these two RTL experiments stimulated students to focus their attention on the features of the graphs rather than on the involved physics quantities. This interpretative analysis was confirmed by the individual conclusion before (Q8) and after the last classroom discussion (Q9).

Students' Conclusions Before the Final Classroom Discussion

After the quantitative experiments performed with the EM Atwood's machine, students wrote their individual conclusions in the tutorial (Q8), before the last classroom discussion. Almost all students (82 of the 87 students, i.e., 94% of them) proposed their individual conclusion, and just 6% of them skipped this task: this represent a first interesting results, since almost all the students were engaged until the end of our activities, despite not all of them answered to some questions proposed in the previous steps. Moreover, the sequence of experiments and the comparison between peers led students to focus on different aspects involved in the observed phenomena, summarized in the Figure 11.

About half of students (51% of cat. D), described the performed experiments focusing on the parameters (weight or falling height) that produce a "*variation of signal*", or "*a variation of magnetic field*". These descriptions emphasize the produced changes, without highlighting the role of time in the EMI phenomena, confirming a result well known in literature according to which students confuse the variation of a physics quantity with the time variation of that specific physics quantity. In the remaining half of answers (49%), students introduced *velocity* among the physics quantities involved in the observed processes. In fact, the category C (divided in three subcategories) relates the EMF with the magnet speed inside the coil: "*the EMF detected when the magnet crosses the coil depends on velocity*" (10%), or "*the EMF is influenced by velocity, weight and falling height*" (7%) or "*the EMF is directly proportional to the velocity*" (8%).

The remaining two categories add further interpretative elements. The category B introduce the idea that the magnetic field influence the electric field and that such influence depends on the speed of the magnetic field: "*magnetic field influences the electric field. The faster is the magnetic field, the bigger are the influences of the magnetic-field*" (7%). In these statements, learners include only the field in their description and not the involved physical objects. Finally, in the category A (2%), students focused on the quantities that remains constant during the process, linking the shapes of graphs to the parameters of EM Atwood's machine: "*since the magnet and the field lines are the same in all the experiments, the area is constant*"; "*the flux is constant and this explains that the*

Table 7. Classification of 87 students' individual after the last classroom discussion

Category	Examples
A1: EMF depends on the variation of field-lines' flux.	*"the variation of field lines is more or less rapid when we change the falling height or the counterweight"; "if the magnet speed increases, also the field lines increase and, consequently, the EMF", "there is a time-variation of magnetic field lines", "the faster is the variation of field-lines' flux and the higher is the EMF value that we measure"*
A2: Equal flux of field lines before and after the passage of magnet.	*"The flux of the entry field lines is the same of the flux of the exit field lines"*
B1: EMF depends on the time variation of the magnetic field lines.	*"There is a time variation of field lines generated by the magnets"*
B2: The variation of field lines depends on the falling heights or on the counterweights.	*"The variation of field lines is more or less rapid when we change the falling height and the counterweight"*
C1: The peaks asymmetry depends on the different magnet speed.	*"The width of the first peak is different from the second one because the magnet entry speed is different from the exit one"*
C2: The peak depends on the magnet speed.	*"Peaks amplitude and width depend on the magnet speed"*
C3: The peak depends on the falling heights and on the counterweights.	*"Peaks amplitude and width depend on the falling heights and on the counterweights"*

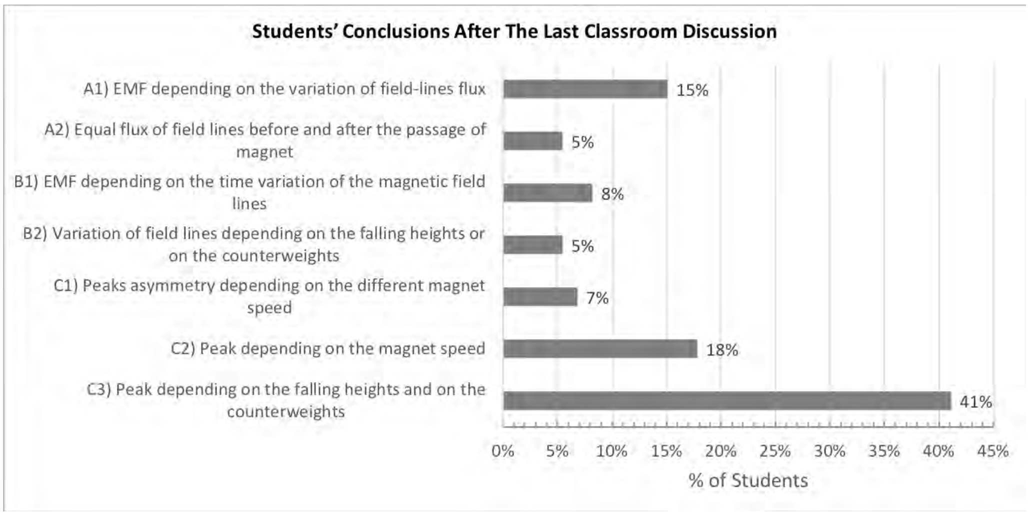


Figure 12. Categories of students' individual conclusions after the last classroom discussion

height of peaks decreases if their width increases and vice-versa".

Students' Conclusions After the Final Classroom Discussion

After the individual conclusion, we involved all students of each class in a final classroom discussion, where they shared their ideas and their individual or small group conclusions. After this classroom comparison, students were asked to summarize individually their ideas about the concepts and processes underlying the FNL law (Q9). Table 7 and Figure 12 summarize the results obtained by the qualitative analysis of all the 87 individual conclusions given by students after the last classroom discussion. We can observe new and interesting interpretative models that appear now (see categories A and B). In fact, after the last classroom discussions 1/3 of students links the EMF signal to the time-variation of the magnetic field lines (Category B1), to the variation of field lines (Category B2) or to the variation of the field-lines flux (Category A1 and A2). Such results confirm the outcomes of students' conclusions after the POE cycle on EMI, because students investigated on their own the EMI phenomena after the problem-solving activities and they found autonomously that EMI phenomena are linked to the magnetic field flux, but they introduced again such kind of ideas only after the classroom discussions. In fact, the category A1 and A2 associate directly the EMF to the "flux of field lines" while the categories B1 and B2 associate the EMF to the time variation of field lines, where the role of flux is implicit and not clearly expressed as in the previous categories. However, Figure 12 shows the 2/3 of students' conclusions classified in the categories C, in which they show a descriptive approach. Anyway, also in these cases, students' answers show a learning progression, since they link the features of the graphs (and in particular of the observed peaks) to the speed of the falling magnet (*"different absolute values of entry and exit peaks height"*).

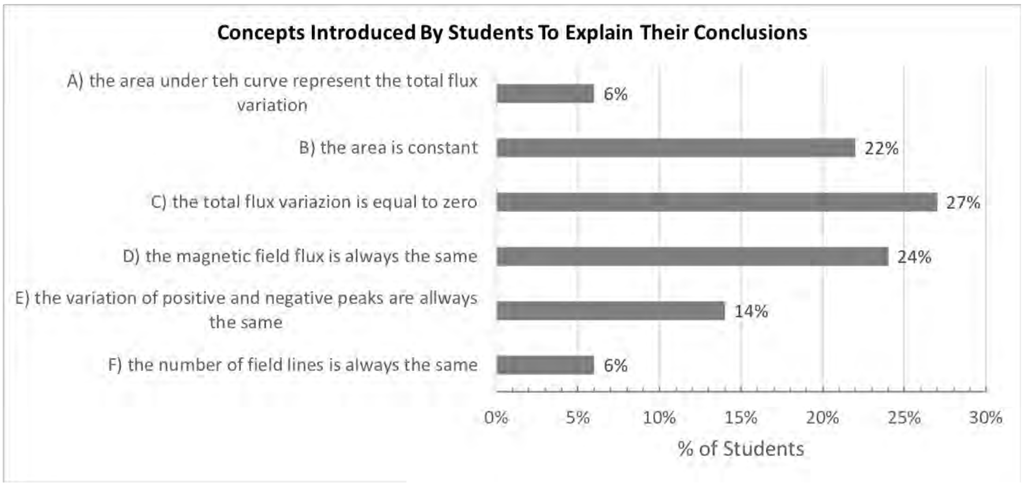


Figure 13. Non-exclusive categories of concepts introduced by students to explain their conclusions (after classroom discussion)

The analysis of students' answer summarized in the Table 7 and in Figure 12 shows that our sequence of experiments and in particular the two RT experiments activated a learning progression (in different forms and levels) for all students starting from which it is possible to construct new and more structured knowledge. The obtained results are particularly relevant if we consider that all the involved students were not introduced to the concept of magnetic field and of EMI before these activities. The engagement of students is confirmed by their personal investigations conducted in some part of the sequence, whose effects are clearly demonstrated by the results obtained in the conclusions of the POE cycle on EMI (Q5a-d) and in the final individual conclusions after the last classroom discussions (Q9). These results confirm the assumed effectiveness of integrating the IBL and RTL approach with the use of POE cycles.

A final interesting result arising from students' conclusions regards the area under the *EMF vs time* signal (Figure 13). In fact, more than half of students (49 of the 87 involved students) spontaneously linked the area under the curve to the magnetic flux. This high level of formalization represents an interesting result of the *Real-Time* activities proposed in our research.

LEARNING OUTCOMES

Summarizing the results obtained in our sequence, the involved students constructed empirically the fundamental concepts of magnetic field and field lines drawing the compass-needle orientation near a magnet. This first result (considerable if we take into account that they had never studied magnetic phenomena before this study) was constructed starting from the local perspective of the magnetic poles, without analyzing in the first exploration global symmetries (as for example the axial or the north-south symmetry). Almost all students were stimulated by the comparison between peers, sharing the representations and the main important features that they observed, so that they reached a global vision of field lines at the end of the Activity C. This important result allowed them to construct the conceptual references necessary to explore real situations of EMI by means of problem-solving activities. In fact, the representative models (constructed by students) of the magnetic field influenced the methods and the conduction of the explorative activities on Emi (E1 and E2), stimulating the passage from the operative definition to the construction of an interpretative model (Scaife & Heckler, 2007). While at the beginning of Activity E1 most of students (more than 66%) focused only on the relative motion between magnet and coil, the analysis of the causes for the observed phenomena shifted (at the end of Activity E2) the attention of more than half of students (59%) towards the role of "*field line variation*" or "*field line variation in time*".

The evolution of students' ideas was stimulated by a sequence of tasks conducted through appropriate tutorials: experimental explorations performed in small groups, followed by individual re-elaborations and then by classroom discussions. The levels of formalization observed progressively after each specific activity on EMI confirm this analysis: for example, after POE cycle on EMI (Activity E2) the majority of students concluded that Faraday-Neumann-Lenz law is produced by "*field line variation, and then magnetic field flux variation*", and this represented a first improvement if compared with the initial analysis proposed to explain the causes of EMI in terms of relative motion between magnet and coil (Activity E1). These results demonstrate the role of our operative approach which allowed students to deal with some important conceptual difficulties of EMI, as for example the relative motion between magnet and coil (Bagno & Eylon, 1997; Maloney et al., 2001; Zuza & Guisasola, 2013). The final high-level of explanations reached by a significant number of students in terms of magnetic flux and area under the induced signal confirms the important role of our experimental sequence and, in particular, of *Real-Time* experiments in the formalization processes of EMI phenomena. These results need an in-depth analysis, for example clarifying the meaning of magnetic field flux that implies the relation between magnetic field lines and the area enclosed by the coil, or specifying the relationship between time and variation of flux.

The *Real-Time* activities, conducted with tutorial based on POE strategy, were efficacy for an important number of students who reached an almost complete vision of EMI. At the same time, such activities had a positive impact also for those students that remained at a descriptive level (providing them with an important number of phenomenological explorations on which a coherent interpretation can be constructed).

The electromagnetic Atwood's machine experiment promoted a high level of formalization giving to students a strong opportunity to pass from qualitative descriptions to formal interpretations of EMI through the Faraday-Neumann-Lenz law, moving progressively their attention from the effects of EMI phenomena to their causes (i.e., the time variation of magnetic field lines or of the magnetic field flux).

CONCLUSIONS

The research based (RB) educational sequence of experiments on electromagnetic induction (EMI) was planned according to the model of educational reconstruction (MER). We proposed this sequence to ten classes of Italian secondary school students, using inquiry-based explorative hands-on activities on EMI, an electromagnetic Atwood's machine and an online free data acquisition system. In this paper we have analyzed in particular the impact of *Real-Time* experiments on the comprehension of EMI phenomena (conducted in an IBL learning environment, using POE tutorials), focusing on the role played by the time variation of the magnetic field lines through the area enclosed by the coil. The use of low-cost and easy to use data acquisition system allowed us to involve students (also) without particular experimental abilities and experiences.

The data analysis shows clearly that the sequence of hands-on explorations and the *Real-Time* electromagnetic Atwood's machine led students to explain the observed EMI phenomena in terms of variation of magnetic field lines or of magnetic flux (RQ1). Moreover, the main outcomes demonstrate the impact of *Real-Time* experiments in the formalization processes of the Faraday-Neumann-Lenz law, based on the role of time-variation in the electromagnetic phenomena (RQ2.1).

The last conclusions, given spontaneously by students at the end of the sequence, show the idea that the area under the induced signal is related to the magnetic flux. Even if these results need further analysis (for example about the meaning of magnetic flux and its relation with the area under the EMF signal), they show the important role of our sequence of activities and, in particular, of the quantitative Atwood's machine experiments in the activation of important conceptual processes (RQ2.2).

The IBL sequence of tasks and experiments, the tutorial based on POE cycle and the small group works/discussions offered students the opportunity to overcome the well-known conceptual knots according to which the EMI is produced by the relative motion between magnets and coils (clearly appeared after the first hands-on problem solving on EMI) and moved their attention towards the variation of the magnetic field lines and towards magnetic flux (RQ3).

In conclusion, this study shows the educational contributions given by our sequence of hands-on activities centered on *Real-Time* electromagnetic Atwood's machine experiments, since it helped the involved secondary school students to analyze various qualitative and quantitative aspects related to EMI. Even if various aspects need further investigations, the final results show the contributions of *Real-Time* experiments in the activation of students' learning processes when they analyze EMI phenomena in which the time variation (of the magnetic field flux) plays a crucial role.

The study here presented demonstrates the effectiveness of combining IBL strategies with POE cycle in *Real-Time* experiments. In fact, they offered students the opportunity to gain a meaningful understanding of the EMI phenomena and to pass from phenomenological descriptions to formalization processes, overcoming many of the conceptual knots highlighted by international literature. The positive results (here described) stimulate the development of active learning proposals on EMI employing these methodologies, taking into account also the difficulties that a significant part of students experienced in the formalization processes. Such difficulties suggest, in particular, the opportunity to integrate in the future this sequence (or similar) with modelling activities for the construction of magnetic flux concept (i.e., the core of FNL law).

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