History of Physics as a Tool to Detect the Conceptual Difficulties Experienced by Students: The Case of Simple Electric Circuits in Primary Education

Published version:

DOI:10.1007/s11191-014-9676-z

*[*Leone M. History of physics as a tool to detect the conceptual difficulties experienced by students: the case of simple electric circuits in primary education. *Science & Education*, vol. 23 (2014), p. 923-953. DOI 10.1007/s11191-014-9676-z*]*

History of Physics as a Tool to Detect the Conceptual Difficulties Experienced by Students: The Case of Simple Electric Circuits in Primary Education

Abstract The present paper advocates the use of History of Science (HoS) into the teaching of science in primary education through a case study in the field of electricity. In this study, which provides both historical and experimental evidence, a number of conceptual difficulties faced by early nineteenth century physicists are shown to be a useful tool to detect 5th grade pupils' conceptions about the simple electric circuits. This result was obtained through the administration of schematics showing circuital situation inspired to early 1800s experiments on the effects of electric current on water electrolysis and on the behaviour of magnetic compasses. It is also shown that the detecting of pupils' alternative ideas about electric current in a circuit is highly dependent on the survey methodology (open ended questions and drawings, multiple-choice item, connecting card work, and history of science tasks were considered in this study) and that the so-called "unipolar model" of electric circuit is more pervasive than previously acknowledged. Finally, a highly significant hybrid model of electric current is identified.

1 Introduction

The advantages of introducing History of Science (HoS) materials into the teaching of science has been advocated by a large number of scholars within the science education community. As recently emphasized by Galili (2011), the argumentation for using the HoS evolves with time, reflecting the cultural changes, and research discourse taking place (Matthews 2000, Galili 2008). Current research seems to focus on three main thematic axes, that is (1) promoting science learning, (2) understanding the nature of science, and (3) studying the historical approach in the institutional instructions and the textbooks (de Hosson and Schneeberger 2011). Despite the intensive support for using the HoS in science teaching, however, "the issue continues to be complex and controversial" (Galili 2011; see also Monk and Osborne 1997; Galili and Hazan 2001).

Under the first axis, i.e. promoting science learning, the history of science may become a tool to detect, and possibly overcome, the conceptual difficulties of the students. This approach, recurrent within the constructivist literature, is rooted in the recognition of a similarity – as opposed to a close "identity" (Galili 2011) – between the ontogenesis of children's thinking and the phylogenesis of scientific development throughout history.[1]

In fact, a strong interpretation of a "recapitulation thesis" is not supported by the available evidence on the actual historical development of scientific concepts,[2] and further work is needed to elucidate the origin of the similarity. However, whether or not it is caused by a transition from a perceptually dominated thinking (common to children's and early scientist's reasoning) to a

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[1] See for example: Dedes (2005); Driver and Easley (1978); Hosson and Caillarec (2009); McDermott (1984); Romdhane (2007); Viennot (1979); Vosniadou and Brewer (1987).

[2] For discussions about important differences between children's thinking and historical development of scientific concepts see, for example, Gauld (1991); Vosniadou and Brewer (1987); Wandersee (1985); Wiser and Carey (1983).

conceptually dominated thinking, as it has been frequently argued,[3] this similarity likely makes the history of science “a useful heuristic device for anticipating some students’ conceptual difficulties” (Wandersee 1985). This is especially true for the history of physics, where a number of studies have shown that the theoretical controversies between scientists of the past could help us to anticipate student’s ideas in the same content area (Sequeira and Leite 1991; Seroglou and Koumaras 2001; Wiser and Carey 1983).

By relying on the above reported similarity between children’s thinking and scientific development throughout science, this paper reports about an experimental study aimed at exploring whether the construction of tasks derived from HoS is likely to offer insights on students mental models about simple electric circuits at the primary school level, and therefore at studying if the HoS is really a useful heuristic device for detecting and, at best, anticipating student’s ideas in this specific area of physics and in this specific age segment of the student population. Since a wide variety of diagnostic techniques have been employed by science education scholars to study children’s ideas about electric circuits, this study, besides addressing a particular mode of using HoS in the science education field, pursued also the broader goal of addressing the influence of methodological factors on study outcomes concerning the popularity of primary students’ mental models of scientific concepts or phenomena.

In this work, the conceptual difficulties faced by early nineteenth century physicists to study electricity phenomena were used as the basis for the construction of tasks to detect and anticipate primary school students’ conceptions about electric circuits. These tasks, however, are not intended to be mere transpositions of historical experiments or controversies to an educational setting. The approach here followed does not assume that student’s conceptions recapitulates scientists ideas throughout history, and it is in some sense similar to that pursued by Nersessian (1992) among others, i.e. that “the historical processes provide a model for the learning activity itself”. Rather than looking at students ideas as a recapitulation of the historical process, HoS should be viewed as “a repository of knowledge of how to go about constructing, changing, and communicating scientific representations” (Nersessian 1992, 54). It is here argued that, besides a “fundamental recasting of how we view the role of the history of science in the science education context”, this approach also calls for a *fundamental recasting of the history of science itself* for science education purposes.

An example of recasting, to arrive at the development of HoS tasks that are able to inform us about children’s spontaneous ideas, will be discussed in the “Findings” chapter below. The findings will be preceded by a pair of background chapters devoted to the two cornerstones of this experimental study: the available evidence on children’s spontaneous ideas about electric circuits, and the account of some aspects of the early 1800s history of electricity.

2 Educational background: children’s spontaneous ideas about electric circuits

Although the literature addressing students’ conceptions about simple electric circuits has been focusing on secondary level students, the studies devoted to primary school pupils are steadily growing up.[4] Most of the early studies focused on the assessment of the models of electric current circulations among children. These studies revealed a number of learning difficulties on physical quantities (current and voltage), conceptual knots (e.g. the concept of closed circuit), and forms of reasoning (the linear and sequential views of circuit as opposed to the system view). A number of

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[3] Expositions of this idea can be found in, among others, Driver et al (1985); McCloskey and Kargon (1988); Monk and Osborne (1997); Nersessian (1989); Seroglou et al (1998).

[4] Examples of studies addressing primary school pupils conceptions about simple electric circuits include Azaiza et al (2006); Cepni and Keles (2006); Cosgrove et al (1985); Driver et al (1994); Galili et al (2006); Grotzer and Sudbury (2000); Jabot and Henry (2007); Jaakkola and Nurmi (2008); Kallunki (2009); Kukkonen et al (2009); Malamitsa et al (2005); Summers et al (1998); Tiberghien and Delacote (1976).

studies, besides addressing these difficulties, managed to improve teaching and learning with a focus on guiding the student to a system view of electric circuit.[5]

Out of this body of literature, the use of HoS materials is very rare. One notable exception is Azaiza et al (2006), where it is briefly emphasized that a “certain similarity between the philo- and ontogenesis with regard to the understanding of electrical current may suggest a different approach to teaching of electricity essentially incorporating the history of science” (p. 67).

According to many authors (e.g. Driver et al 1994, Summers et al 1998, Borges and Gilbert 1999, Galili et al 2006), four main models on current circulation in a battery and bulb circuit are identified:

1. the *unipolar model*, where the electric circuit is not closed;
2. the *clashing current model*, where the current flows from both poles of the battery and the light is sometimes explained in terms of the “clash” of the two currents;
3. the *current consumption model*, where there is less current in wire going back to the battery since it is “consumed” by the bulb;
4. the *“scientific” model* of constant current throughout a closed circuit.

A number of slight variations of the above models had been reported. For example, a further version of the current consumption model had been at times identified. Besides an “attenuation model”, whose characteristics are that of the above current consumption model, sometimes it is also identified a “sharing model”, where identical lamps in series are predicted to be all the same brightness, for example, but current is not regarded as conserved (e.g. Osborne 1981, 1983; Shipstone 1984,1985).

Galili et al (2006) identified two more hybrid models. The first one is a sort of intermediate between the unipolar model and the other ones since “within this model pupils drew a closed circuit, but showed current flowing solely in one of the two wires connecting the bulb with the battery” (p. 837). The second hybrid model is instead a mixture of the clashing currents model and the unidirectional models since “the current leaves the pole of the battery [and] flows through most of the circuit whereas in a small part of the circuit the current runs in the opposite direction” (p. 837).

Based on simulation and laboratory activities Jaakkola and Nurmi (2008) refined the current consumption model by identifying four submodels, three of whom could be considered as rough approximations toward the scientific model. Beyond a consumption model, they found indeed a constant-current model, a surface model, and a preliminary Ohm model. Alternative classifications of the models had also been suggested.

Grotzer and Sudbury (2000) argued for grouping the models “by the causal assumptions that one needs to make in order to understand them and the conceptual leaps needed in understanding causality in order to progress from one set to the next” (p. 4).

A large scale study about the degree of popularity of the models (Cosgrove et al 1985) shows that only about 5 per cent of a sample of 10-yrs old children use the unipolar model, while the clashing current, current consumption and scientific models display comparable levels of popularity.

Yet, even a cursory comparative analysis of the literature reporting data about pre-assessments shows a remarkable degree of variation in the popularity of the models with 3rd – 5th grade age-groups across studies (Tab.1). A comprehensive analysis of the reasons behind this variation is outside the scope of this paper. Anyhow, cultural factors, methodologies of data collection, or a combination of both, might be at origin of the observed discrepancies. As regards the methodological factors, a number of data collection procedures have been indeed used to investigate primary school children’s conceptions about electrical circuits. These include multiple choice tests

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[5] For example, Azaiza et al (2006); Duit and von Rhöneck (1998); Fera and Michelini (2011); Psillos (1998).

(by far the predominant method), open-ended questions, oral interviews, drawings, laboratory and/or simulation activities.

models	**Some pre-assessment experimental studies on current circulation models**											
	Grotzer& Sudbury (%)	Azaiza et al (%)				Cepni& Keles (%)	Galili et al (%)		Jabot & Henry (%)			Jaakkola & Nurmi (%)
unipolar	37	29.5	12.5	90	93	58	10	0	2	0	2	14
clashing	41	7.5	25	0	0	4	25	17	60	64	55	41
consumpt.	7	7*	0	0	0	2	50*	60*	18*	21*	31*	11
scientific	0		0	0	0	0						8
others	15	56	18.5	0	0	26	15	0	0	0	0	27
no answer	0	0	44	10	7	10	0	23	0	0	0	0
grade(size)	4(27)	3(30)	4(40)	4(80)	4(40)	5(50)	4(40)	4(40)	3(63)	4(49)	5(108)	4&5(64)
method	interview	written open questions				open questions drawings	written open questions		yes/no & drawings test			multiple choice test

Tab 1 Popularity of models of current circulation in a number of pre-assessment experimental studies on 3rd, 4th and 5th grade children (full bibliographical details about these studies are listed in the references section). The asterisks (*) denote circumstances where the classification method adopted does not allow to distinguish between current consumption model and scientific model. Data marked with an asterisk represent therefore the total percentage of children holding either a current consumption or a scientific model.

3 Historical background: some aspects of the early history of electric circuit studies

Prior to testing for children’s understanding of simple electric circuits, a study was performed to analyse the main early 1800s developments of electrodynamics. The goal of this study was to provide an historical account to be qualitatively compared with children’s spontaneous ideas, and to be used as a source of core ideas to guide the construction of HoS tasks and the interpretation of children’s ideas. It is important to emphasize that, in case of significant parallels or analogies, the HoS inquiry is here proposed in order to help teachers to anticipate some of children’s ideas about the electric current in a circuit, rather than to help students’ interpretations or ideas about currents and circuit.

Since the main conceptual difficulties faced by students concern the concepts of closed circuit and electric current, it seemed reasonable to compare the historical record of the emergence of these ideas in the context of the history of physics with the outcomes of the science education studies on students’ spontaneous ideas. Drawing on the most relevant primary sources, this study focused therefore on the immediate aftermath of two key moments in the history of electrodynamics that is Alessandro Volta’s development of the “pile” in 1799 (Bevilacqua and Fregonese 2000-2003; Pancaldi 2003) and Hans Christian Oersted’s discovery of electromagnetism in 1820 (Oersted 1820, Sarton and Oersted 1928).

3.1 On the effects of the single pole of a battery

The development of Volta's battery was motivated by the previous studies carried out in Bologna by the physician Luigi Galvani. Drawing on his electrophysiological experiments where frog's muscle-nerve preparations were stimulated by atmospheric and static electricity, and where frog's legs were connected with metal arcs, Galvani developed the idea that the muscle is a sort of Leyden's jar and that nerve conduction and muscle motion are due to the presence of a form of electricity in the animal tissues. Galvani's experiments aroused great interest and eventually led to a major controversy on the "animal electricity".

Among the first scientists to replicate these experiments was Volta who, after having initially supported Galvani's theory, came up with the idea of explaining the muscle contractions with the effect of a "contact" electricity (as opposed to an animal one) resulting from the use of arcs made of two different metals. With the goal of providing a conclusive proof of the correctness of his contact electricity model, that did not require a living environment, Volta devised in 1799 his "pile", that is an "artificial electric organ", as he called his battery in his well known March 1800 letter to the Royal Society.

As a consequence of the above experiments on the Galvanic arc and the subsequent development of the Voltaic pile, the idea of continuously moving electricity in a closed "voltaic circuit" entered the domain of physics. The emergence of the concept of electric circuit, however, was somewhat hampered by the former static electricity knowledge deriving out of experimental observations on the interaction between charged bodies and the effects of electric discharges produced by an apparatus such as the Leyden's jar. One of the consequences of the difficult transition between static electricity domain to the novel dynamic electricity field, embodied by the idea of the Volta's pile as a sort of self-rechargeable Leyden's jar, was the attempt to produce chemical and magnetic effects out of the single pole of a battery (Benseghir and Closset 1993; Viennot 1996/2001).

As an example of chemical effects, there was water electrolysis, that is the decomposition of water into hydrogen and oxygen by voltaic current, first obtained by William Nicholson and Anthony Carlisle in 1800, soon after Volta's discovery (for a report about a successful water electrolysis experiment preceding the invention of Volta's pile, by a powerful *electrostatic* generator based on friction, see de Levie 1999).

In his *Report on the Galvanism*, the influential French naturalist Georges Cuvier wrote about the attempts to produce gas by the direct action of the single pole of a battery (Cuvier 1801; Wilkinson 1804, 149). After reporting about the capability of Volta's pile to yield the production of gas when the two extremities of the battery are put into communication with the water, the French *savant* reported that he was puzzled by a number of phenomena, namely the fact that if we place the extremities of a pile inside a volume of water, oxygen and hydrogen gases appear only at a certain distance from the wires. And, most importantly, the facts that the gases appear out of points mutually far apart, and that each gas appears always out of a specific extremity of the pile, are not easily explained under the assumption that oxygen and hydrogen are produced by the very same water molecule. These observations, as reported by Cuvier, led some scientists to believe to be on the verge of a "new chemistry" and some other ones to suspend the judgement.

Yet, Cuvier remarked, whatever their beliefs, all scientists had to begin their experiments by the same kind of research, that is by looking if it is possible "to produce the two gases in separate waters". These preliminary experiments led to the observation that "if the waters are absolutely isolated, no gases appear". In order to produce the gases, Cuvier reported, it is necessary "to put [the waters] into communication by a metal wire" (Cuvier 1801, 320). Similar observations were repeated again, for example, by Antoine Libes, professor of physics at the Ecole Centrales in Paris (Libes 1801, 402;1803), and by naturalist Eugène Patrin (1810). In 1811, J.D. Maycock emphasized also that, if Humphry Davy's influential hypothesis that chemical affinity and electrical attraction are identical forces (a few years earlier Davy arrived at this conclusion after his experiments leading to the decompositions of potash and soda into the new metals of potassium and sodium through the use of a large voltaic battery),

> [it is] difficult to explain why decomposition is never produced by a single wire, however powerful may be the battery, with which is connected; why decomposition is never effected, either by common or galvanic electricity, except when *two* conductors, in different electrical states, are made to act on each other (Maycock 1811, 24-25).

Notwithstanding the negative results of above experimental setup, still in 1825 the Geneva physicist Auguste De La Rive, checked if the single pole of a battery was able to produce the water electrolysis. It is worth to remember that De La Rive was one of the key figures within the voltaic electricity studies. He eventually became one of the main advocates of the chemical theory of the Volta's pile (Kipnis 2003), that is the view that chemical changes are necessary for the production of an electrical tension or a current, if the circuit is closed. In the Nineteenth Century, a long-lasting controversy opposed the chemical theory to the contact theory, i.e. the view, first put forward by Volta himself (see the beginning of section 3.1), that the action of the pile was due only to a contact force arising when two different metals were put into contact (Kragh 2000, Kragh and Bak 2000, Kipnis 2001).

In one of his earliest contributions to the voltaic electricity studies, De La Rive reported the available "facts … about the necessary and favourable conditions for the production of decompositions by the pile" (De La Rive 1825, 192). The first of these facts was the requirement that the solution to be decomposed is part of a "closed voltaic circle" and that, as a consequence of this, the solution is traversed by electric current. While De La Rive did not doubt that a battery require a closed voltaic circle to produce a current, he still felt the need to complete his account of the requirements to be met with a reference to the possibility that the single pole of a battery could still produce the water decomposition. "Thus", De La Rive, added:

> I ascertained that it is impossible to produce chemical decompositions by immersing only one pole of the pile in the liquid, and it is not possible as well by immersing the two opposite poles of two different piles (De La Rive 1825, 193).

Out of this negative result, De La Rive posed the question about how to reconcile it "with the idea that the decompositions are only due to the electric tension in which the liquid is assumed to be". The result of this experiment and its implications were also later reported by another advocate of the chemical theory, the Paris physicist Antoine-César Becquerel (1835, 377).

As for the magnetic effects to be obtained by one single pole of a battery, Oersted himself, that is the author of the discovery of electromagnetism through the observation of the deviation of a magnetic needle induced by an electric current (see the next section 3.2), reported in 1820 that it seemed demonstrated by his experiments that "the magnetic needle was moved from its position by the galvanic apparatus, but that *the galvanic circle must be complete, and not open, which last method was tried in vain some years ago by very celebrated philosophers*" [emphasis added] (Oersted 1820, Sarton and Oersted 1928).

To what celebrated philosophers Oersted referred is presently unclear. One possible candidate is S.P. Bouvier (1803) from Brussels who, however, could hardly be considered a "celebrated philosopher". Bouvier attached an iron support to the top of a pile and set a magnetic needle on its pointed end. When he touched the bottom of the pile with one hand and brought the other hand to the needle, it moved. As remarked by Kipnis (2005), "the circuit was evidently open, and a keen reader could have recognized Bouvier's effect as electrostatic" (see also De Andrade Martins 2001).

Another candidate was Gian Domenico Romagnosi, more a jurist and amateur physicist rather than a celebrated philosopher. Romagnosi's 1802 experiment has been sometimes considered a sort of anticipation of Oersted's 1820 discovery of electromagnetism through the observation of the deviation of a magnetic needle induced by an electric current. According to Romagnosi's report:

> Having constructed a voltaic pile, of thin discs of copper and zinc, separated by flannel soaked in a solution of sal-ammoniac, he attached to one of the poles one end of a silver chain, the other end of which passed through a short glass tube, and terminated in a silver knob.
>
> This being done, he took an ordinary compass-box, placed it on a glass stand, removed its glass cover and touched one end of the needle with the silver knob, which he took care to hold by its glass envelope. After a few seconds contact the needle was observed to take up a new position, where it remained even after the removal of the knob (Romagnosi 1802a; English translation in Stringari and Wilson 2000, 133).

Owing to the unclear description of the experimental apparatus in Romagnosi's original accounts (Romagnosi 1802a, 1802b), sharp disagreements exist in the historiographical literature about the legitimacy of a priority claim (e.g. Stringari and Wilson 2000, De Andrade Martins 2001, Russo and Santoni 2010, 274). Two remarks are however relevant here: 1) Romagnosi consistently discusses an apparatus where only one end of a metal chain was connected to a Volta's pile, and therefore there was no electric current passing through it (Govi 1869); 2) Romagnosi's remark about the "Galvanic flow" shows that, while he might have actually observed an electrostatic effect, his experiment was not intended to be of an electrostatic nature. While the exact details remain unclear, Romagnosi's experiment suggests, as the previously discussed water electrolysis experiments do, that the relationship between closed circuit and physical-chemical effects of a pile was not as obvious as today.

Since in all likelihood Oersted was not aware of Bouvier's and Romagnosi's experiments, it is possible that the Danish physicist was referring about the research on the relationship between electricity and magnetism undertaken in early 1800s by researchers with whom he had a close acquaintance, such as Jean Nicolas Pierre Hachette, Professor at the *Ècole Polytechnique*, and by Johann Wilhelm Ritter, German physicist as well as Oersted's friend (Kipnis 2005).

3.2 On the "conflict of electricity" and the "dissipation of electric fluid"

As emphasized above, Oersted's discovery of electromagnetism was the second crucial transition between static electricity and dynamic electricity studies. His discovery of the effect of an electric current upon a needle compass demonstrated that electricity and magnetism are not separate phenomena, as it was strongly believed for example around 1600, but are two manifestations of a single effect. This reunification was made possible by the above discussed Volta's discovery of a tool able to produce a steady flow of current electricity and by Oersted's metaphysical speculations. As he wrote about himself, his adherence to the opinion "that the magnetical effects are produced by the same powers as the electrical" was indeed a consequence of his belief in the philosophical principle "that all phenomena are produced by the same original power" (Stauffer 1957).

One of the main results that are directly connected with Oersted's discovery of the mechanical motion of a magnetic needle produced by electric current was the emergence of the telegraph industry. Soon after Oersted's discovery, André-Marie Ampère proposed indeed to construct a telegraph by using as many conducting wires and magnetic needles as there are letters (Ampère 1820, p. 73), and the question arose as to whether long-distance electromagnetic telegraphy is possible. Answering that question will prove difficult. However, the efforts toward that goal provided important knowledge about the electric current in a circuit.

Among the scientists who attempted to understand if "an instantaneous telegraph might be established by means of conducting wires and compasses" figures Peter Barlow, English mathematician well known for his invention of achromatic telescope lenses ("Barlow lenses").

Actually, Barlow's main goal was to throw some light on a major controversy, dating back to late 1700s, concerning the nature of electric charge (Barlow 1825a, 1825b). This controversy opposed the followers of Abbe Jean-Antoine Nollet's two fluid theory of electricity to the ones of Benjamin Franklin's single fluid theory. According to Nollet's view, the two-fluid theory could explain the existence of two distinct kind of electricities, very different from each other, formerly discovered by Charles Francois Du Fay: the vitreous electricity, produced by rubbed glass, and the resinous electricity, produced by rubbed amber. Franklin argued instead that only one electrical fluid existed and that a "minus" or "plus" state of electrification reflects the state of a body having less or more than a normal amount of electrical fluid. One early difficulty of Franklin's view was its failure to explain the repulsion between two bodies carrying resinous electricity (i.e. negatively charged), since the one-fluid model explained this electricity with a lack of fluid. Although this difficulty was later accounted by modifying Franklin's model (by Franz Ulrich Theodosius Aepinus), the controversy between the two models continued into the 1800s (for an account of this controversy for science education goals see Binnie 2001, Furió et al 2004).

The relevance of fluid theories of electricity to the interpretation of Volta's battery was authoritatively stated, a few months after Oersted's discovery, by Ampère (1820), who assumed the electricity as consisting of two distinct fluids and the voltaic battery as an instrument possessing the power of conveying one of these fluids to the one end and the other to the other end. According to Ampère, when the poles of a battery are connected by a connecting wire, "a double current results, the one of positive electricity, the other of negative electricity, parting in opposite directions from the points where the electro-motive actions exists, and reuniting in that part of the circuit opposed to those points" (Ampère 1820, p. 63).[6] Oersted's himself had suggested that "the effect which takes place in [the] conductor and in the surrounding space" should be named "*conflict of electricity*" (Oersted 1820). As another pillar of electromagnetic studies, Michael Faraday, acutely observed,

> This reunion would of course, take place in the wire, and one may be allowed to ask, whether the magnetic effect depends on it, as M. Oersted seems to think, who calls it *the electric conflict*, and also what becomes of the electricities that accumulate in the wire. But from other parts of M. Ampère's memoirs, a very different idea of the electric currents may be gained; the one electricity is considered as continually circulating in one direction; while the other electricity circulates and moves in a current in the opposite direction, so that the two electricities are passing by each other in opposite directions in the same wire and apparatus [emphasis added] (Faraday 1822, p. 112).

In 1825, by using as guides Oersted's discovery, besides Johann Schwigger invention of a "multiplier"(multi-turn coil) to increase the magnetic power of a circuit, and Ampère's idea of a telegraph system, Barlow attempted to understand whether is long-distance telegraphy possible. By measuring the angle of magnetic deviation as a function of the length of the wire, Barlow "found such a sensible diminution with only 200 feet of wire", as at once to convince him of the

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[6] A look at the 1820s and 1830s physics textbooks shows that the poles of the pile are often considered as "indefinite sources of contrary electricities" (Pouillet 1828, 635; Benseghir and Closset 1993, 39; see also Bayle 1836, 541) or "inexhaustible sources of opposite electricities" (Webster 1837, 413). In the conductors between the poles, "the accumulated electricities meet incessantly" (Lamè 1837, 172; Benseghir and Closset 1993, 39), or "will occasion a continual recomposition" (Webster 1837, 413), or, again, "the opposite electricities tend to destroy one another and, if the intermediate liquid is a substance incapable of decomposition, the equilibrium would be restored and the motion of the electricities would cease altogether" (Barzellotti 1808, 359-360).
As one chemistry dictionary explained, "if two metal wires, connected with the two ends or poles of the pile, are brought closer to each other, the two opposite electricities will meet at the point of contact of the two conductor. [After] the contact, the two electricities kept producing at the two sides of the pile, and at joining within the conductor to form a continuous current" (Pelletan 1824, 372).
Interestingly, if one widens the search at the contemporary meteorology, discovers that the meeting of contrary electricities was thought to be the cause of lightning: "the lightning is certainly due to the meeting of two contrary electricities, accumulated within close portions of two different clouds" (Lamé 1837, 81; see also Pouillet 1825, 401), in accordance with the view that the clouds are "good conductors, while the air with which they are surrounded is a bad conductor", that is "immense isolated conductors" (Olmsted 1832, 164).
Ideas closer to the modern views about the battery in a closed circuit were developed at the same time as the above conceptions. A notable example can be found in the writings of Leopoldo Nobili, one of the main Italian physicists of early 1800s (Leone, Paoletti and Robotti 2011). In 1822, he explained that "once completed the voltian circuit, we should no longer believe that the zinc and copper ends are a permanent home of the contrary electricities as when they were isolated". As soon as the circuit is closed, of the former equilibrium, nothing is left "out of direction and velocity of movement" (Nobili 1822, 167). As the French physicist Jean Peltier said, in his 1836 address to the Academy of Sciences in Paris, "pile and conductor constitute a unique system where all the parts are interdependent so that the electromotor is no longer under the same conditions when, for example, the conductor is changed" (Peltier 1836, 476).

"impracticability of the scheme" (Barlow 1825a, 105). Out of this negative result, he was led to investigate the cause of the diminution and the laws to which it is subjected, with the hope that this could throw some light on the one-fluid vs. two-fluids controversy.

> If […] this diminution arose from a dissipation of the electric fluid in its course, then, on the hypothesis of a single fluid, the action ought to be much stronger at that part of the wire nearest to the positive pole of the battery, than at the other extremity. While, if two fluids are admitted issuing from both extremities of the battery, the action at the centre of the wire should be much less than at the parts adjacent to the two poles (Barlow 1825b, 271).

Barlow managed therefore to measure, by means of three compass needles, the magnetic deviation at different distances along a wire connected with the poles of a battery. One needle was placed at the middle of the wire (at C in figure 1) and the other two near the ends of the wire (at B and D, figure 1). Besides finding that the current strength was inversely proportional to the square of the distance, Barlow discovered that, for each length of the wire,

> it appeared that the three compasses were equally affected in each experiment [see figure 2]; the slight differences observed being ascribed […] either to error of observation, or some difference in their respective conditions. From this it follows, that the diminution of effect, when a greater length of wire is employed, is not to be attributed to an accidental dissipation of the fluid; the compass, which was upwards of 400 feet from either extremity of the wire, being equally affected as those only 7 feet distant (Barlow 1825b, 271).

In order to compare the deviations produced with different lengths of the wire, it was necessary to compensate for the systematic error introduced by the battery during the progress of the experiment. This was done by estimating the relative power of the battery before each measurement, through the effect of a short conducting wire on another compass (at A, figure 1; see also the column "deflection of standard compass A", figure 2). As observed by Barlow, "from thence it was computed what the deviations would have been, had the power of the battery remained constant" (Barlow 1825b, 272).

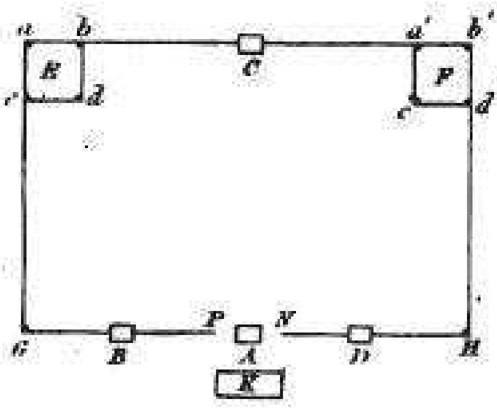
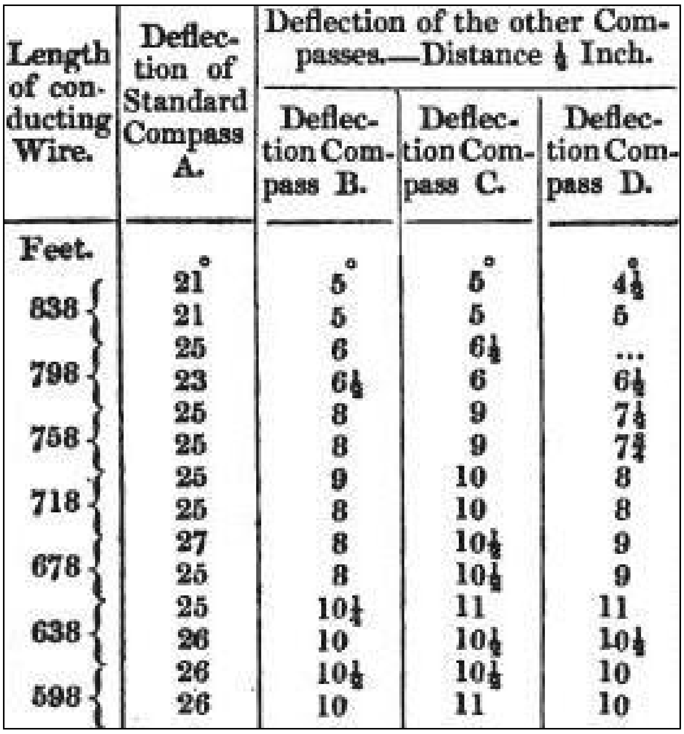


Fig 1 Barlow's circuit to measure the electric current in different points of a wire through the measurement of deflection of magnetic needles placed in B, C, and D (Barlow 1825a).



Length of conducting Wire.	Deflection of Standard Compass A.	Deflection of the other Compasses.—Distance ½ Inch.		
		Deflection Compass B.	Deflection Compass C.	Deflection Compass D.
Feet.				
838	21°	5°	5°	4½°
	21	5	5	5
798	25	6	6½	...
	23	6½	6	6½
758	25	8	9	7½
	25	8	9	7¾
718	25	9	10	8
	25	8	10	8
678	27	8	10½	9
	25	8	10½	9
638	25	10¼	11	11
	26	10	10½	10½
598	26	10½	10½	10
	26	10	11	10

Fig 2 A sample of Barlow's original measurements of needle deflection at points B, C, and D, showing that the intensity of current does not change throughout the circuit, whatever the length of the wire is (Barlow 1825a).

Still in 1825, Barlow's finding about the intensity of current in a circuit was supported by the experiments carried out by the Paris physicist Becquerel, aimed at establishing "[whether] the intensity of the electro-dynamic force is the same anywhere in a wire or whether it decreases from the poles of the pile toward the central part of the wire" (Becquerel 1826, 428).

Becquerel considered a circuit where the pile *MM'* (figure 3) was connected to the metallic wire *PN*. By connecting a segment of the wire, e.g. *ab*, through a couple of equal copper wires, e.g. $a\alpha$ and $b\beta$, to a galvanometer made by a magnetic needle suspended within a multi-turn coil, Becquerel observed a deviation of the needle from its initial direction due to the electric current circulating in the wire of the galvanometer. If a couple of wires from the ends of another segment of wire *of identical length*, e.g. *c'd'*, is connected to the galvanometer in such a way that a second current in the opposite direction is produced there, Becquerel found that the needle is not displaced from its position of normal equilibrium. As reported by Becquerel, since "the difference between the intensity of current in *a* and in *b* should be equal to the difference between the intensities in *b'* and *a'*", it should be concluded that "the intensity of current is either the same in all points of the wire, or decreased in arithmetical progression" (Becquerel 1826, p. 429-430).[7]

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[7] In his review paper about Barlow (1825a), J.-F. De Montferrand, professor of mathematics and physics at the Royal College of Versailles, observed that Barlow's experiment did not support the view that the electric fluid dissipates along its course and reaches the minimum at the negative pole nor the one based on two electric fluids starting at both poles and producing the minimum magnitude of electric current at the middle of the circuit. However, the second view "is clearly incorrect since the intensity observed in each point is due to the sum of the actions of the two currents started at both poles. In order for this sum to be constant, it is required, as it was shown by Becquerel, that the intensity of each current is either constant or changing in an arithmetical progression" (De Montferrand 1825, 284).

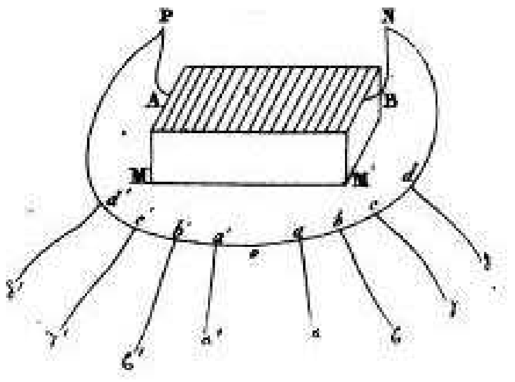

Fig 3 Becquerel’s circuit to compare the electric current produced by a battery (MM’) in different segments of a wire (*oa, ab, bc, oa’, a’bi, b’c’*) through the measurement of deflection of the magnetic needle of a galvanometer connected with couple of wires starting from the extremities of the segments (e.g. $c'\gamma'$, $d'\delta'$) (Becquerel 1826).

Thus, when George Simon Ohm entered the field of the laws governing the electric circuits – in the years 1825-1827 – it was already established, mainly through Barlow’s work, that the intensity of current does not change throughout the circuit (Kipnis 2009). In fact, however, Barlow’s discovery that the effect of the electric current upon a magnetic needle dramatically reduced after a limited distance put at rest for a time all the attempts to construct a long-distance electromagnetic telegraph. Things started to change in 1830s, by Joseph Henry and Philip Ten Eyck’s discovery that the current strength is actually inversely proportional to distance, not to distance squared (Schiffer 2008), and, most importantly, that Barlow’s difficulty could be overcome by employing a high-intensity battery able to activate at distance an electromagnet with a coil of many continuous turns, and the subsequent Charles Wheatstone and William Fothergill Cooke’s patent of the first practical electric telegraph (Turner 1983).

The “dissipation of fluid” idea was, however, not over, as evidenced, for example, in a 1854 law report of patent case on the telegraph, where Chief Justice Taney summed up the early difficulties in electromagnetic telegraphy by stating that the efforts were hampered by “the fact that the galvanic current, however strong in the beginning, became gradually weaker as it advanced on the wire” (Telegraph Case – United States Supreme Court 1854, 324).

3.3 General remark

The generalization of the concept of closed voltaic or galvanic circle (which emerged with the development of Volta’s pile) to the subjects of the chemical and magnetic effects produced by a battery, and the emergence of the concept of constancy of the electric current throughout the circuit (which was made possible by the previous Oersted’s accomplishment) out of the theoretical controversy about the electrical fluids, seems to make a further case for the claim that a similarity exists between children’s thinking and historical development of scientific concepts. Just as in the history of electricity studies there was a time when the working of the battery was understood without resorting to one or both of the above concepts (sections 3.1 and 3.2), also the scientific model of electric circuit among children seems to follow earlier spontaneous models lacking concepts that bear strong similarities with the historical counterpart (section 2).

A word of caution is in order. The historical account above provided does not prove rigorously that the same steps occurred in the evolution of scientific concepts among the scientists of the past and among the children of today (dealing moreover with different phenomena, theoretical backgrounds, goals, materials and so on). It is even possible that problems like the effects of the single pole of a battery and the equality of current in a circuit were considered trivial or uninteresting by the majority of scientists. What remains, however, is a suggestive similarity, whose significance might lie, as it has been sometimes assumed, in the fact that the shift from the thinking of the naïve to the thinking of the expert practitioner involves “the same kinds of conceptual change as does theory change in the history of science” (Wiser and Carey 1983). And, if a certain degree of similarity between the two domains exists, we might expect that HoS driven materials could help us to enrich our appreciation of children’s spontaneous ideas with respect to the standard methods of detecting such ideas without paying attention to the historical dimension of science. This expectation will be verified in the experimentation below.

4 Aims of the study

A small sample of Italian primary school students was chosen to carry out an analysis of some aspects of their understanding of simple electric circuits. Through this analysis, it is expected to explore what is the role of methodological factors in determining study outcomes concerning the popularity of the models on current circulation. Besides addressing the role of methods as written tasks, open questions and discussion/interviews, this study will also explore to which directions does the use of ideas from HoS for the construction of tasks within established methods affect the research results concerning the students’ alternative ideas. To this goal, this study will drew on materials derived by the history of some relevant early 1800s researches on the electricity produced by batteries.

5 Material and methods

The participants to the experimental study were 78 fifth grade students (10 yrs old), from four classes of one average urban Italian primary school, that had no prior formal education on electricity before the study took place. It is important to emphasize that, at time of this study, the Ministry of Education national guidelines for the primary school mainly listed “learning goals” to be achieved by children at the end of grades 3 and 5 (MPI 2007). The new guidelines do not substantially alter the earlier ones (MIUR 2012) and, as for the natural and experimental sciences, do not mention the electricity as one of the physics field through which achieve the stated goals. Unlike the recent guidelines, the former 1985 Elementary School Programs (DPR 12 February 1985, n. 104), explicitly suggested experimenting on electricity and magnetism, building batteries and bulbs electric circuits, and studying the difference between insulating and conductive materials through direct tests. The programs also included the working principles – electricity included – of household appliances.

A subset of the sample (Group 1, n = 37 students from two classes – Group 1a and Group 1b – taught by two different science teachers) was studied by this author in the classroom jointly with the class’ science teachers in Fall 2011. Both teachers had about 15 years of teaching experience in primary school. They got a permanent position before the current mode of appointment through a MA degree course in Primary Education Sciences became fully operational, but had participated to a large number of in-service training courses, particularly on science education topics. Another subset (Group 2, n = 41 students) was studied in Fall 2012, upon this author guidance, by a young substitute teacher as a part of her master’s thesis in Primary Education Sciences devoted to electric circuits and learning. Since the experimental activities on this second subset turned out to be only partially overlapped with that of the subset directly studied by this author, only the results discussed in section 6.1 below concern the whole sample. On the contrary the results presented in sections 6.2 – 6.4 are entirely based on Group 1 students.

In order to provide an assessment of the role of methodological factors, four different diagnostic methods were employed: drawings, work with connecting cards, multiple choice item, yes/no and open question about electric circuit schematics. The fourth method was constructed upon the basis of the historical development of electricity studies in early 1800s. The whole sessions were taped with a digital recorder, and the relevant discussions were later transcribed.

In each subset of the sample the unit began with a presentation of the materials to be used, i.e. one standard C battery (1.5 V), one flat battery (4.5 V), a 2.2 V, 0.25 A bulb and a 4.8 V, 0.3 A bulb, without providing any relevant cue about them. After a brainstorming session, in which the students discussed and shared opinions about the objects (names, daily life uses, nature, functions, etc.), each battery and bulb was closely inspected by each child.

At the end of the presentation phase, the children were asked to consider only a pair of objects, the C battery and the 2.2 V bulb. They were provided with sheets of paper and instructed to “draw the battery and the bulb”, to “show how the bulb may be lit”, and to “make use of symbols to help understanding what happens” (the assignment was also written on the classroom chalkboard). The same procedure was followed with the second pair of objects, the flat battery and the 4.8 V bulb. The content of the message was designed to make it as neutral as possible, in order to not influence the children, and nonverbal cues were kept to the minimum. The sheets of paper were collected and the drawings were categorized in classes, according to the electric circuit model that can be deduced by the information contained in the drawings and, when present, in written explanations, captions and so on. The drawings were later digitized.

The second session of work started with a multiple choice question on alternative graphic representations of the electric current in a circuit (Cosgrove et al 1985; Kallunki 2009), which was readily collected and categorized, and continued with a simulation work with connection cards (for applications of this methodology see Testa, Michelini and Sassi 2006, Kallunki 2009). The classes were subdivided in small, 4-pupils, groups. As it is well known, small groups offer indeed “ample opportunity for students to share their ideas and decide on promising strategies to solve learning tasks” (Huber 2003).

Each group was handed over b/w pictures of batteries and bulbs glued on supports of cardboard and was asked to show how the bulb and the battery should be connected in order to lit the bulb. A number of copper wires with alligator clips was left aside, on the teacher desk: each group could take as many wires as desired, without any cues from this author or the teachers. At the end of the connection work, each artefact was photographed and each group was asked to explain the reasons why it was connected in a given way. In case of differences between the cardboard circuits constructed by a given group and the previous drawing made by a member of the group, a call for explanations followed.

Afterwards, the whole session was devoted to the actual construction of the models of circuits, drawn by the children and built with the connection cards by the groups, and to the collective analysis of the outcomes. The whole set of models was previously scrutinised and subdivided in classes of similar circuits. Each class was built by the children, subdivided again in small groups.

Finally, in the fourth session, the children were provided with two sheets of paper, one at a time, each one containing a schematics of a battery-bulb circuital setup, derived from the above discussed HoS study, a yes/no written question, and the requirement to give reasons for their choices. Also in this case, the sheets were in turn collected, categorized and, eventually, digitized. To each administration followed the experimental test of the circuit and the analysis of the outcomes, which was, as the previous three sessions, wholly taped.

6 Findings

As discussed in the “Educational background” section, four main models on current circulation in a battery and bulb circuit are identified in literature: unipolar, clashing currents, current consumption, and scientific. The reported data about pre-assessments, obtained through multiple choice tests, open-ended questions, oral interviews, drawings, laboratory and/or simulation activities shows a remarkable degree of variation in the popularity of the models with 3rd – 5th grade age-groups across studies (Tab.1).

With goal of assessing the role of methodological factors in determining study outcomes on the popularity of the models on current circulation among children, the sample of this study was studied through a number of these diagnostic techniques: drawings, multiple-choice item, simulations with connecting cards, yes/no and open question about electric circuit schematics. This later technique consisted in the construction of tasks based on the similarity, discussed in section 3, between children's thinking and historical development of the scientific concepts of closed circuit and of constant electric current in a circuit.

6.1 Drawing and multiple-choice item phase

As outlined in the previous section, at the end of a presentation phase on the materials to be used (batteries and bulbs), the children were instructed to "draw the battery and the bulb", to "show how the bulb may be lit", and to "make use of symbols to help understanding what happens".

The advantages of using a drawings technique for exploring children's spontaneous ideas, avoiding the use of cues associated with a given model, have been addressed in a large number of studies. Among the different reasons given are: providing the children a quick and enjoyable method; providing alternative form of expression for children who have difficulty expressing their thoughts verbally; avoiding the children feel constrained to match their knowledge with that of the researcher (e.g. Köse 2008).

As a matter of comparison, the drawings phase was followed by the administration of a multiple choice question on alternative graphic representations of the electric current in a circuit formerly used in large scale study about the degree of popularity of the models (Cosgrove et al 1985).

Each drawing produced by the children following the presentation phase was inspected and then placed into one of four categories according to the level of understanding about the current circulation it displayed (unipolar, clashing currents, current consumption, scientific).

In agreement with part of the sample of Israeli pupils studied by Azaiza et al (2006) through a questionnaire, and the sample of Turkish students studied by Cepni and Keles (2006) through open-ended questions and drawings, this study showed a marked preference for the unipolar model among 5th grade children that had no prior formal education on electricity (over 70% both in Group 1 and 2: see table 2). Significantly, a large proportion of the Group 2 children displayed their preference for the unipolar model by drawing a battery and a bulb within a flashlight. Furthermore, many of the drawings classed as "others" (since they were not easily categorized in a class or another, or did not follow the assignment) showed signs of an underlying unipolar model.

This outcome was observed after the pupils were asked to consider the C battery and the 2.2 V bulb (for two typical examples of drawings showing the unipolar model see figure 4). A second situation was presented to the students with the goal of exploring the possible effects of drawing a scenario based on a battery of different symmetry. After the first step was completed, the students were therefore instructed to consider a flat battery and a 4.8 V bulb. In this second situation, the unipolar, clashing currents, and scientific models got comparable results (between 10 and 20% of Group 1). Actually, most of the children (about 60% of the subsample) did not provide enough data (e.g. direction of electric current) to place the drawing into one specific model of current circulation. This latest result is largely an effect of the experimental protocol: since the focus was on the reliability at the expense of completeness, the message delivered to the children kept conceptual cues to the minimum.[8]

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[8] E.g., Cepni & Keles (2006, p. 277) made use of open-ended questions containing keywords as "electricity", "circuit", "series connection", "direction of current", "pole of the battery", and leading questions as "does the amount of current change?".

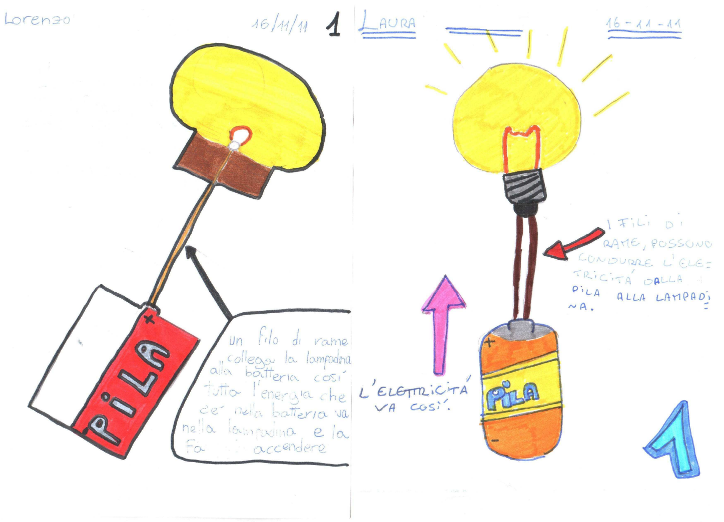


Fig 4 Drawings made by Lorenzo (*left*) and Laura (*right*) showing a unipolar view of the battery-bulb system.

Several days after the drawing phase, a multiple choice question on alternative graphic representations of the electric current in a circuit was administered to the children. In the item task, adapted from Cosgrove et al (1985, p. 249), the children were asked which of the submitted alternatives best represented their view of the electric current in a circuit.

The whole set of alternatives showed a battery and a bulb connected by two wires. If a given pupil selected the answer "there will be no electric current in the wire attached to the base of the battery", he was classed as a unipolar model supporter. Other possible answers were: "the electric current will be in a direction toward the bulb in both wires" (clashing currents); "the current will be less in the 'return' wire" (current consumption); "the current will be the same in both wires" (scientific).

As it is shown in table 2, the administered item produced sharply different results from the previous drawing phase. The most popular model turned out to be the clashing currents one (about 50% of the sample), while the consumption and the scientific models were found in about 20% of the sample, and the unipolar answer was chosen by one pupil out of ten. In fact, Cosgrove et al's large sample cross-age study gave comparable results for 10 yrs old children, most notably as regards a lack of popularity of the unipolar model (5%) as compared to the other three (each one close to 30% of the sample).

	Drawing (*n* = *77*)			**Multiple-choice item (*n* = *74*)**		
	Group 1 (%)	Group 2 (%)	**Total (%)**	Group 1 (%)	Group 2 (%)	**Total (%)**
unipolar	72	80	**76**	9	12	**11**
clashing	3	–	**1**	48	61	**55**
consumption	–	–	**–**	18	15	**16**
scientific	–	–	**–**	21	12	**16**
other	8	20	**14**	3	–	**1**
no answer	17	0	**8**	–	–	**–**

Tab 2 Comparative popularity of current circulation models as obtained with free drawings and multiple-choice item.

Since the former phase had evidenced a large number of drawings with just one wire between one pole of the battery and the bulb, one might be tempted to conclude that the comparative popularity of current circulation models inferred by drawings with one wire and schematics showing two-wires circuits has little relevance. It should be noted, however, that this conclusion would be valid unless such a comparative popularity was actually used in literature, e.g in the above mentioned Cosgrove large-scale study, to draw conclusions also about the popularity of the unipolar model. The multiple-choice item phase was therefore intentionally designed as a choice among circuits with two wires in order to check whether our sample yielded results comparable with that of other studies using the same criteria. As above reported, a qualitative agreement actually exists. Thus, on the one hand we might interpret this as a sign that the earlier studies show a certain degree of reproducibility. On the other hand, however, we are legitimated to conclude that this reproducibility is bought at the cost of systematically underestimate the popularity of the unipolar model.

6.2 Connecting card and experimental work phase

At the end of the session on the administered item, the classes were subdivided in five small, 4-pupils, groups for carrying out the connection cards work. Each group was asked to show how the card bulb and the card battery should be connected by alligator clips in order to light the bulb. Differently of the drawing phase, at the end of the connecting card group work all the groups had connected the C-battery with the bulb through a pair of wire.

Two different solutions of similar popularity were found: either each pole of the battery was connected with the bulb through a wire (e.g. this solution was chosen by three subgroups of Group 1a), or just one pole (the positive one) was connected to the bulb through two wires (solution chosen by two subgroups).

The second strategy – two wires out of one pole – is clearly reminiscent of some of the drawings made in the earlier session, where the unipolar model took sometimes the form of multiple wires going out of the positive pole of the battery. On the contrary, the first solution – each pole connected by its own wire – was scarcely popular in the earlier drawing session. Furthermore, this solution does not seem to derive out of the presence of two connectors on the card battery and the consequent application of the principle that everything given is to be used. The card battery supplied to the children was indeed obtained by gluing a b/w photograph of a real C-battery to a cardboard base. Thus, as in the real C-battery, only the positive pole had a easily identifiable connector.

It should be emphasized that the wires were freely available on the teacher’s desk. This was done so as not to predetermine the circuital setups as it would necessarily had been if a given number of wires was supplied to the groups. While this diagnostic tool is not intended to provide a definitive assessment of the incidence of a given circuital model among children, it offers a valuable insight into the above reported issue of the inconsistent results of the drawing and multiple-choice testing. A significant example of this is provided by the following exchange between this author and some of the children (here and elsewhere in this paper, quotations are translated from the original Italian language to English):

> Author [A.]: Here we have the group made by Lorenzo, Gerardo, Stefani and Laura. By analyzing the drawings we see that Lorenzo drew one wire going from the pile to the bulb. Gerardo drew two wires going from one side of the pile to the bulb. Laura also drew two wires from the plus of the pile to the bulb. Finally, Stefani drew three wires, still from the plus of the pile to the bulb. Now [by the connection cards], you have made a project where you see also a wire going mysteriously from…
> Lorenzo: … the minus of the pile to the bulb.
> A.: How did you come out with this brilliant idea?
> Lorenzo: Because maybe, we thought, *if [the bulb] takes from both sides it can take more energy*.

> Laura: Because in the bulb there are two sort of wires. And so, these ones can be the plus and minus [of the pile].
> A: Why did you think about this now and not before? What was different from now?
> Laura: It came to my mind looking at this [the connecting card], and then I saw that it had two more here [within the bulb]. […]
> A.: And instead done in this way here, with the wires that stem from the same side? According to you, the bulb may light if connected according to the drawings?
> Lorenzo: *Yes, but maybe the bulb will light a little more* [if connected as the connection cards].

Since both free drawings and multiple-choice activities were carried out on the same sample of pupils in sequence (in order to avoid working with excessively small samples), the detected transition toward more mature views (i.e. less incidence of the unipolar model) might be taken to be a case of "learning by testing". An analysis of children's explanations out of their no-experimental-feedback connection cards activity provide compelling reasons to think otherwise.

The interviews with the children show that the prevailing view is that one connection wire between battery and bulb is enough to obtain the lighting of the bulb. This agrees with what found in the drawings. However, "better two wires than one" (as rendered by another pupil, Simone). That is, as Lorenzo said, "if the bulb takes from both sides it can take more energy". Not surprisingly, therefore, when the children were shown, in the multiple choice item phase, a schematics of a battery and a bulb connected by two wires most of them saw no reason to believe that "there will be no electric current in the wire attached to the base of the battery". It is therefore legitimate to conclude that the multiple-choice test dramatically underestimated the popularity of the unipolar model.

In the following session of work, each group assembled the circuital setups, suggested during the former activities, with real batteries and bulbs. This was the first time when the children had the possibility to carry out actual experiments, to review the evidence from such experiments, to try alternative connections, to discover by themselves that a closed circuit was required to light the bulb, and to collect notes in their notebooks. It goes without saying that this experimental work was of the utmost importance in the development of children's own thoughts about the concept of electric current in a circuit.

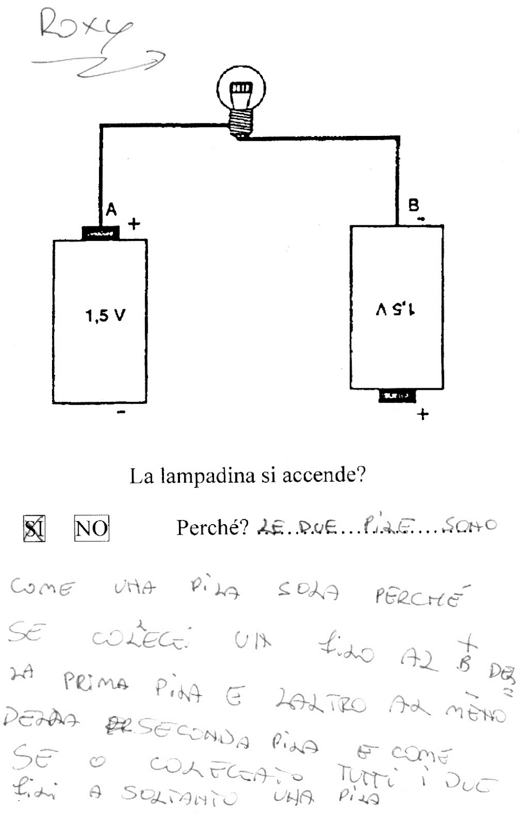
6.3 De La Rive task

Previous studies show that challenging students' views is not an easy task since the new concepts often coexist with spontaneous ideas rather than replacing them, and the students' responses to empirical evidence often does not yield long-lasting effects (e.g. on this latter point see Gauld 1989). Rather than studying the effect of the above reported didactic sequence, the following session of this study focused on using HoS materials, inspired by the history of electricity studies in early 1800s, to elicit further details on childrens' spontaneous ideas about battery-bulb connections.

The starting point, of course, is the observation that, as elsewhere, also in the field of electrodynamics a certain degree of resemblance exists between children's thinking and the development of scientific ideas throughout history (section 3.3). To become an heuristic tool in science education, however, the HoS device should be able to anticipate some new facts about students ideas rather than merely producing with hindsight episodes or moments of history resembling to students ideas.

It is important therefore to emphasize that by HoS material it is not meant neither a faithful diachronic reconstruction of a given experiment or theory nor its rational synchronic reconstruction. Under the first approach, the account provided in section 3.1 is of no direct use in primary school science education on electric current since Cuvier's and De La Rive's experiments are placed within the very exotic context of explaining how Volta pile could produce the water electrolysis. And if the second approach is followed, the account of section 3.1 is just, at best, a footnote of a rational reconstruction of history (Lakatos 1971) since it shows a number of scientists struggling with a false problem given the internal history of Volta battery (where a galvanic circle must be closed); but a rational reconstruction of history just removes those developments sometimes paralleled by children's thinking and therefore deprives the history of its heuristic potential. By HoS material it is instead meant, in some sense, the "deconstruction of history", through reference to specific conceptual knots, and the construction of tasks where these knots are adapted to a different historical and mental context.

The first activity was aimed at answering the following question: given the above reported didactic sequence, should we expect that the unipolar model is really over among the children involved in this study? The children were given the schematic of a circuit, inspired by De La Rive (1825), where "the two opposite poles of two different piles" are connected with a bulb, and were asked "would the bulb light?". The schematic, which is adapted from Benseghir and Closset 1993 (for a similar task see also Asami et al 2000), is shown in figure 5 jointly with the answer provided by Roxy.



La lampadina si accende?

☒ SI ☐ NO Perché? LE DUE PILE SONO COME UNA PILA SOLA PERCHÉ SE COLLEGI UN FILO AL + B DELLA PRIMA PILA E LALTRO AL MÈNO DELLA ~~DE~~ SECONDA PILA È COME SE O COLLEGATO TUTTI I DUE FILI A SOLTANTO UNA PILA

Fig 5 Roxy's answer to the De La Rive's task ("two batteries are like a single battery. If one connects a wire to the plus of the first pile and the other one to the minus of the second pile is like connecting both wires to one pile").

In spite of the fact that the circuit was open, most of the students responded affirmatively to the question about whether the bulb will light if the batteries are connected as in the De La Rive task (n = 29, 83% of Group 1). Among those who said that bulb would not light, only one pupil – Aurora – explained that to light the bulb "the piles should be connected by a [second] wire". Other pupils gave the correct answer for the wrong reason. For example, Lory explained that the bulb would not light "because both wires should start from the positive pole". Independently of the numerical outcome, the major interest of the test lies in the explanations given by the children (table 3).

Main classes of explanation	%	Examples
Two different battery poles / energies are required	46	*“To light the bulb it requires a plus and a minus, and the piles offer them to it”* *“It is like having just one rotated pile”* *“Two batteries are like a single battery. If one connects a wire to the plus of the first pile and the other one to the minus of the second pile is like connecting both wires to one pile”* *“It lights because one connects one wire to the plus and one to the minus. However, if one connects both wires to the minus the bulb would not light”* *“The bulb requires positive energy (+) and negative energy (–)”* *“A+ has more energy than B–”*
Two different bulb poles are required	31	*“A wire connects the plus of the pile with the side of the bulb, and the other wire connects the minus of the pile with the base of the bulb”* *“The connection is correct because B wire connects under the bulb and the other wire to the side [of the bulb]”*
No matter if a pile is turned	9	*“If one turns upside down the piles the energy comes out the same”* *“Bulbs light even if one is turned upside down”*
It is a matter of copper	9	*“Since the copper is a good conductor of electricity, it sends [the electricity] to the bulb”* *“It lights if one put two pieces of copper wire”*
Two equal bulb poles are required	6	*“It could also light by putting both wires at the base of the bulb rather than one at the side and one at the base”* *“Both wires should be connected either to the side or to the base”*
Only the positive pole works	6	*“The bulb would not light because to light the bulb both piles should be at the plus”* *“Both wires should start from the plus [of the battery]”*

Tab 3 Classes of explanations given by the children to justify their answer to the “De La Rive task”.

As the table shows, a number of different reasons were provided by the children. Two thirds of them suggested one of the above reasons, while the remaining children suggested a couple of explanations at the same time. The most frequently reported explanation stressed the need of connecting both a plus and a minus pole of the batteries with the bulb (Ignacio: “to light the bulb it requires a plus and a minus, and the piles offer them to it”), and emphasized that the battery poles are the actual sources of electricity/current/energy, wherever these poles may be (Roxy: “two batteries are like a single battery”; see figure 5). Clearly, such an explanation suggests that a linear causal effect between battery and bulb is in action. Under this effect, an agent, variously named “electricity” (e.g. by Mara), “current” (Oussama), and “energy” (Simone)”, is believed moving between the battery and the bulb.

As it is well known, “the linear causal effect between battery and bulb does not imply a closed circuit” (Duit and von Rhöneck 1998). This later condition is rarely mentioned by the children (in fact, just one pupil, Aurora, emphasized the need for a closed circuit), notwithstanding the previous experimental activity. On the whole, the closed circuit condition is far less important to these children than connecting the bulb to two different sign poles. The main significance of this historically-derived task lies therefore in its having *revealed that a closed circuit setup can hide a firmly held unipolar view*.

About one third of the children paid attention to the polar nature of the bulb (e.g., as reported by Stefani, the bulb lights because “a wire connects the plus of the pile with the side of the bulb, and the other wire connects the minus of the pile with the base of the bulb”). This kind of explanation is likely a consequence of the previous experimental work with bulbs lacking lamp holders.

In the final part of this task each group, after a number of attempts, assembled De La Rive’s circuit and eventually arrived to the closed circuit requirement for obtaining the lighting of the bulb. The children were asked about the reasons behind their choice. One pupil that had given a positive answer to “De La Rive task” explained that the bulb should light “since one wire started from the plus [pole] and the other one from the minus [pole]; one arrived at the base and the other one to the side [of the bulb]”. Another pupil that had answered negatively explained instead that “the bulb should take energy from the plus and the minus of one battery and from the plus and minus of the other battery”. Following a class brainstorming, the children concluded that in order to light the bulb, both poles should be on the same battery. Alternatively, another pupil, Ignacio, suggested that the bulb might light by adding a third wire between the free poles of the batteries.

6.4 Barlow task

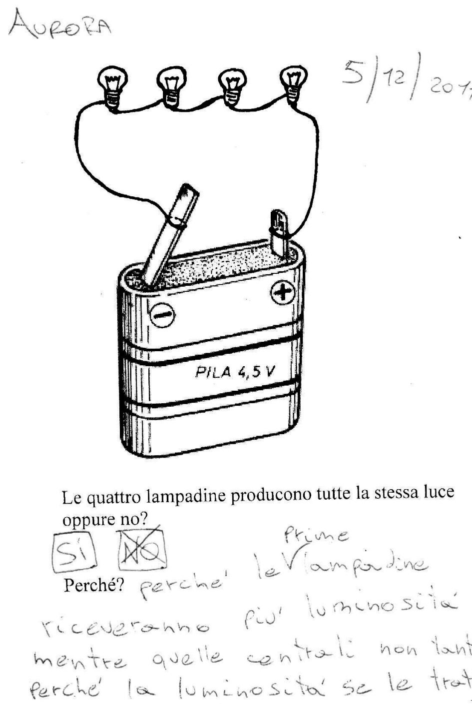
The second historically-guided activity was aimed at understanding the electric current models being used by the children when considering a schematic showing a closed circuit. As for the preceding task, also this one is subject to the same observations concerning the status of the HoS materials submitted to the children. Thus, the account above (section 3.2) was intended to summarize some of the early 1800s ideas about the way the current circulates within a closed circuit connected to the poles of a battery. Of course, the strategy adopted by Barlow and Becquerel to solve the issue were part of a well-defined scientific environment, deeply influenced by the recent Oersted’s discovery of the effects of the electric current on a magnetic needle.

Independently of the experimental strategy, however, Barlow’s experiment is of particular interest since, differently of Becquerel’s experiment, it was motivated by the long-standing one-fluid vs. two-fluids controversy that began in the pre-Volta pile years. The available data about children’s spontaneous ideas on the electric current in a circuit, where clashing currents out of two poles and consuming current out of one pole figure prominently among the accepted models (sections 2), suggest that it is just the theoretical fluid controversy, motivating Barlow’s experiment, rather than the actual Barlow’s (or Becquerel’s) electromagnetic methods, that has the potential to cast at least some light on children’s ideas. In this vein Barlow’s task, rather than being the fairly accurate blueprint of Barlow’s experiment, was inspired by its conceptual structure.

The children were given the classic schematic of a circuit conceptually inspired by Barlow (1825a, 1825b), whose goal was just to estimate the electric current magnitude in different parts of a closed circuit. Differently of Barlow’s setup, where he measured the angle of magnetic deviation as a function of the length of the wire between the battery poles and the needles, the children were asked what were their expectations about the brightness of a number of bulbs (four bulbs, in fact) connected in series with a battery and, therefore, at difference distances from the battery poles (the schematic is shown in figure 6 jointly with the answer provided by Aurora).

The rationale of this approach is that, on the one hand is desirable to avoid the unnecessary complications that might derive from the use of a phenomenon involving the relationship between electricity and magnetism to understand the children’s electric current models (for a teaching sequence at the middle school level making use of magnetic needles within a similar context see Benseghir 2004). On the other hand, the relative bulbs brightness can serve as a powerful analogy for a twofold goal: first, to provide the children an easy-to-understand tool to spell out the consequences of their electric current model; and, second, to provide the experimenter a way to give *a whole new meaning to a standard circuital schematic in order to change it into a novel diagnostic tool to detect children's spontaneous ideas*.

As Barlow was confident that his experimental setup was able to settle the one-fluid vs. two-fluids controversy by measuring where the action of the electric current upon a magnetic needle was much stronger (that is, near the positive pole of the battery or near the negative pole), it is felt that a conceptually similar circuit, where a number of bulbs are connected in series with a battery, might shed light on the circuital models of the children. The conceptual similarity lies in the fact that just as in Barlow's experiment the expected outcome was a consequence of the effect of a given length of wire upon the dissipation of the electric fluid in its course, in this task the expected relative lighting of the bulbs was a consequence of the particular model of circuit used by the children.



Aurora

5/12/2011

Le quattro lampadine producono tutte la stessa luce oppure no?

Sì [✓ NO]

Perché? perche' le prime lampadine riceveranno più luminosità mentre quelle centrali non tanto perché la luminosità se le tratte

Fig 6 Aurora's answer to the Barlow's task ("the outer bulbs will receive more light than the central ones because [the outer ones] retain all the brightness").

About half of the sample (n = 16, 46% of Group 1) responded affirmatively to the question of whether one might expect that the four bulbs would all emit the same light. Most of these children provided explanations consistent with the scientific model (n = 10, 29% of Group 1). As a matter of fact, the whole set of answers to this task revealed three models of current circulation – current consumption, clashing currents, and scientific – of comparable popularity (table 4), in agreement with Cosgrove et al (1985) large sample cross-age study. In one instance, the current consumption model reduced in fact to a "source-sink" unipolar model: Matteo reported indeed that "only the first three bulbs give the same light. If each bulb lights like with a 1,5 V C-battery: 1,5 V x 3 = 4,5".

Models of current circulation	%	Examples
Current consumption	34	*“Only the first three bulbs give the same light. If each bulb lights like with a 1,5 V C-battery: 1,5 V x 3 = 4,5. Thus, only the first three.”* *“The bulbs do not receive the same energy. It is not enough for all the bulbs”.* *“It could be that a bulb absorbs power from another.”*
Clashing currents	29	*“If the bulbs are lit it means that the plus- and minus- electricity must pass in all the bulbs evenly.”*
Scientific	29	*“All four bulbs produce the same light. However, less light will be produced.”*

Tab 4 Main models of current circulation revealed by the “Barlow task”.

A close analysis of the answers provided by the children, however, revealed also a number of interesting and unexpected “hybrid” models covering about 30% of the sample (table 5). Of a special significance is a hybrid model displaying properties of both the current consumption and the clashing currents models. About one out of three children belonging either to the current consumption or the clashing currents classes (table 4) actually belong to both classes since their response to the Barlow task contain structural elements of both models. For example, according to Marco “almost all electricity is taken by the two outer bulbs, and the inner ones will get less electricity”, that is clashing currents consumed by the bulbs. In a similar fashion, according to Aurora “the outer bulbs will receive more light than the central ones because [the outer ones] retain all the brightness”.

Models of current circulation	%	Examples
Current consumption + clashing currents	11	*“The outer bulbs will receive more light than the central ones because [the outer ones] retain all the brightness.”* *“Almost all electricity is taken by the two outer bulbs, and the inner ones will get less [electricity].”*
Clashing currents + asymmetry	11	*“There are two wires, one that starts from the plus and another from the minus. Thus, they make a different light. The plus makes more light than the minus.”*
Other	9	*“The energy is passed from one bulb to another […] The bulbs that are at the beginning and at the end are lit more, but then they pass the energy to the other [inner] bulbs and therefore [the energy] becomes equal.”*

Tab 5 Hybrid models of current circulation revealed by the “Barlow task”.

About another third of the children belonging to the clashing currents class reported instead that there is an asymmetry between the currents starting from the positive and negative poles. According to Eleonora, “there are two wires, one that starts from the plus and another from the minus. Thus, they make a different light. The plus makes more light than the minus.”

Finally, three pupils showed not-easily classifiable, yet very worth discussing, mixed views.

Madalina’s answer is unclear since it contains a pair of contradictory statements. While the first one’s content is consistent with the scientific model (“the wire passes from all four bulbs and all give the same light"), the second statement is consistent with the current consumption model ("and the first [bulb] turns on and makes a different light").

Valentina, instead, put forward a view curiously reminiscent of Becquerel and De Monteferrand's remarks (see footnote 2 above). At a first reading, her answer contains one element of the scientific model of electric circuit, that is the view that all the bulbs emits the same light because something (called by her "energy") is equally shared by the bulbs: "there are two wires, one of which starts from the minus and the other part from the plus, and then the energy is distributed in all the bulbs. They will light less". However, the above sentence was followed by a whited out, yet barely readable, explanation: "because half half half half". This "discarded" explanation conveys a new meaning to the previous sentence since four "halfs" make two "wholes", two "energies" moving through "two wires, one of which starts from the minus and the other part from the plus", and equally "distributed in all the bulbs". In short, we have clashing currents and constant intensity of current everywhere, just as would happen in Becquerel's view of the two-fluids model.

The third pupil, Teresa, is uncertain about which alternative is best. She begins her answer by an hypothesis *à la* current consumption ("the energy is passed from one bulb to another"). Then, she seems reasoning in terms of an hybrid clashing current plus current consumption model ("the bulbs that are at the beginning and at the end are brighter [than the inner ones]". At last, she tries to accommodate her expectation that the brightness should be the same within the hybrid model by resorting to a the concept of a transitory period ("but then they pass the energy to the other [inner] bulbs and therefore [the energy] becomes equal").

In assembling the experimental circuit, as a preliminary test, two bulbs were connected with the flat battery without making use of wires. Do the two bulbs light the same? Interestingly, one pupil (Aurora) remarked that, had this setup been provided in the previous task, she would have answered that the bulbs *do* emit the same lights, differently of what she had answered. Since the outer bulbs receive more light than the inner ones (according to the above detected hybrid clashing consuming currents model), as both bulbs are in fact outer bulbs, one might expect – even under an hybrid current consumption plus clashing currents model – that both bulbs emit the same light! Peter Barlow would have provided the same answer, that is the same magnetic deflection would be expected under his hybrid two-fluids model of electric current, had he used just two magnetic needles in the B and D positions (figure 1).

Another pupil, Lorenzo, succeeded in lighting the two bulbs without making use of wires but suggested that such a result was an outcome of the no-wires setup. By this observation, a further clarification about children's current consumption model emerges: while the consumption is usually seen as a consequence of making the current pass through a bulb, sometimes the consumption is associated with the current circulation through a wire, as if there were, to use Barlow's words, "a dissipation of the electric fluid in its course".[9]

7 Discussion

The aim of this study was to investigate the role of methodological factors in determining the popularity of the models on current circulation, and in particular to explore to which directions does the use of ideas from HoS for the construction of tasks affect the diagnostic research results. It is

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[9] I am grateful to one anonymous referee for calling attention to the possibility that an experiment with multiple bulbs could not yield the expected result. A tiny difference in the length of filaments in supposedly identical bulbs could indeed produce a noticeable change in brightness. To some extent, this effect could be reduced by an outstanding property of the human eye, that is the Weber-Fechner law as applied to the power of distinguish differences brightness of objects. Within a reasonable experimental error, when comparing the brightness of different sources of light, the effect of light may be considered indeed as proportional to the logarithm of its intensity (e.g. Hecht 1924).

therefore important to highlight here what this study found about HoS, what it demonstrated, and what it did not demonstrate.

A preliminary point to notice is that this study pursued the approach of exploring the ways in which HoS materials can inform us about children's spontaneous ideas, rather than studying how HoS may be designed to overcome students' conceptual difficulties and measuring the efficacy of this method. The present research, therefore should be seen only as a pilot study concentrating on just one of the possible ways of conceiving the HoS approach in science education. Further, this research has focused on a topics, the electric current, where very rarely diagnosis of spontaneous ideas, HoS approach, and primary school level, meet.

As a first outcome, this study found that the overall results of popularity of the current circulation models were very sensitive to the use of different methods of diagnosis of children's spontaneous ideas, and that the use of HoS materials could seriously affect our conclusions about student's ideas. In studying the spontaneous ideas by means of open ended questions and drawings, by the multiple-choice item, by the connecting card work, and by the HoS tasks, it was indeed found that the popularity of models strongly depends on the method employed for diagnosing.

The results, when using open ended questions and drawings, have shown that the unipolar model far outweighs other models of current circulation. Cepni and Keles (2006) found similar results (see table 1), when a sample of 5th grade Turkish students faced the task of connecting two bulbs and one battery by open ended questions and drawings. If a multiple choice item was submitted to the children, the clashing currents, current consumption, and scientific models prevail, at the expenses of the unipolar model, in analogy with what was found by Cosgrove et al (1985) by the same method.

One possible reason for discrepancy between these first two methods was found through the connection cards work and the following interviews. A number of children explained indeed that while a unipolar connection between one battery pole and bulb was enough to obtain the lighting of the bulb, this is not to say that no current would flow through a second wire from the other battery pole and the bulb. This agrees with the findings discussed by Duit and von Rhöneck (1998) that "the second wire to be found in working circuits in everyday life simply serves to bring more current to the bulb".

The results obtained by the HoS tasks somewhat enriched our understanding of children's spontaneous ideas. The De La Rive task evidenced indeed the persistence of the unipolar model after an instructional session aimed at experimentally showing the closed circuit requirement. By the Barlow task it was found a number of formerly unacknowledged models about current circulation.

Besides providing evidence of a possible methodological bias in previous researches, this study demonstrates that HoS material could help us to better appreciate children's spontaneous ideas. The way in which the scientists of the past planned their experiments to understand how the electric current changes within an electrical circuit are a useful source of inspiration and a good teaching aid to help the present-day teachers to grasp the children's models about the electric current in a battery-bulb closed circuit. But, what's more important, the history of science allows to anticipate formerly unknown children's mental models.

A survey of early 1800s studies about the battery in a circuit has shown that the demonstration that the intensity of current does not change throughout the circuit is due to Peter Barlow (1825). Actually, Barlow expected that either the electric current was stronger close to the positive pole than elsewhere (according to the one-fluid model) or that the electric current was stronger near the positive and negative pole than at the middle of circuit (two-fluids model). It is of interest to note that the first hypothesis closely resembles to students' current consumption model where there is less current in the wire going back to the battery, the only difference being that in Barlow's framework the dissipation of electric fluid is due to the wire itself while in present-day students mental models the consumption of electric current is due to the bulb. Barlow's second hypothesis is instead a sort of ante-litteram hybrid model between the current consumption and clashing currents views. The current study unexpectedly reveals that such an hybrid model actually appears among a number of 5th grade children.

Finally, this study also demonstrates that HoS provides experimental strategies to settle learning difficulties. As it was discussed above, the work with drawings and open questions shows that the unipolar model is likely much more pervasive than previously acknowledged. This study shows that such a model is also firm and not very easily overcome by the experimental evidence in a learning environment. A task where the children are presented an activity conceptually derived from the early history of chemical effects produced by the poles of a battery (De La Rive task) shows that this model keeps showing up even though a session of work aimed at experimentally testing the working of connections and circuits was previously carried out.

8 Conclusion

This study is a contribution to a line of research devoted to better understanding the role of history of science to promote science learning. The results discussed above highlight indeed the benefits of using HoS materials to foster the detection of children's spontaneous ideas. Under the perspective here adopted the educational role of the history of science lies more in its heuristic power to offer insights on children's thinking than in its motivational role to make science more appealing to children or in its power to help students progress in their learning of simple circuits.

However, some limitations of this study deserve attention, the most notable one being the limited size of the sample which precludes the possibilities of generalizing from the findings. As a consequence of this, the findings are tentative at best and call for replication on larger populations. Other limitations of this study are more theoretic in nature. Specifically, it purports to determine if HoS may be of value in a science learning setting without a shared theoretical framework to assess the similarities between scientific development throughout history and children's thinking across the age span from early childhood to young adulthood.

Notwithstanding these limitations, this study provides some empirical evidence as to the effectiveness of history of science to science education and hopefully should stimulate further investigations in this area.

Acknowledgments The author wishes to thank Laura Bassino and Anna Paradiso for their help in setting up the research, and Venera Saida for participating to the collection of data as a part of her master's thesis in Primary Education Sciences at the University of Turin. The author would also like to acknowledge the thorough and thoughtful comments of the anonymous referees who provided helpful suggestions for improving this paper.

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