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Identifying secondary-school students' difficulties when reading visual representations displayed in physics simulations

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ABSTRACT

Computer simulations are often considered effective educational tools, since their visual and communicative power enable students to better understand physical systems and phenomena. However, previous studies have found that when students read visual representations some reading difficulties can arise, especially when these are complex or dynamic representations. We have analyzed how secondary-school students read the visual representations displayed in two PhET simulations (one addressing the friction-heating at microscopic level, and the other addressing the electromagnetic induction), and different typologies of reading difficulties have been identified: when reading the compositional structure of the representation, when giving appropriate relevance and semantic meaning to each visual element, and also when dealing with multiple representations and dynamic information. All students experienced at least one of these difficulties, and very similar difficulties appeared in the two groups of students, despite the different scientific content of the simulations. In conclusion, visualisation does not imply a full comprehension of the content of scientific simulations per se, and an effective reading process requires a set of reading skills, previous knowledge, attention, and external supports. Science teachers should bear in mind these issues in order to help students read images to take benefit of their educational potential.

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Computer simulations: an educational tool based on visual communication

A computer simulation can be understood as a computer-generated dynamic representation of a model of a process, component, or phenomena of the real-world (Smetana & Bell, 2012). Computer simulations are considered tools that mediate and facilitate the relationship between reality and models or theories is the possibility of interaction between students' mental models on a certain topic and the underlying conceptual models in the simulation (Evagorou, Korfiatis, Nicolaou, & Constantinou, 2009; Monaghan & Clement, 1999; Pintó & Gutierrez, 2004). In the last decade, thousands of students

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around the world currently use computer simulations as educational tools in their science classes (Grimalt-Álvaro, Ametller, & Pintó, 2013; Hennessy, Deaney, & Ruthven, 2006; Rutten, van Joolingen, & van der Veen, 2012), and especially in physics' classes (Crook, Sharma, & Wilson, 2015). For these reason, they have progressively become a matter of interest in the field of research in science education, under the assumption that simulations provide specific learning opportunities in certain contexts. First, simulations enable students to deal with virtual phenomena that would otherwise be impossible to observe (Anderson & Barnett, 2013; Honey & Hilton, 2011; Wieman, Adams, & Perkins, 2008), and also that manipulating and modifying depicted elements, parameters, and variables can improve the development of students' models (Ardac & Akaygun, 2005; Dega, Kriek, & Mogese, 2013; Ryoo & Linn, 2012). It has been also demonstrated that simulations can enhance and enrich laboratory work by an optimal combination of real and virtual experiences' (Chang, Chen, Lin, & Sung, 2008; Zacharia, Olympou, & Papaevripidou, 2008), and even outperform real experiences on conceptual understanding (Finkelstein et al., 2005). In this real–virtual combination, Akpan (2002) states that simulations allow to repeat scientific procedures again and again, that in a conventional classroom setting would be too time-consuming or too dangerous, and Lindgren and Schwartz (2009) state that simulations do not only can scaffold inquiry, but also reduce the cognitive load imposed by mental manipulation of spatial topics.

Beyond this set of affordances, the educational impact of simulations have been the subject of numerous studies in science education literature, and a real positive impact on student learning has been identified, only if some conditions are met. The critical review made by Smetana and Bell (2012) stated that the effectiveness of simulations is optimal in those cases where they are used as supplements (that is, not replacing other instructional modes), when they include high-quality support structures, and also when they promote student reflection and cognitive dissonance. In parallel, the review made by Honey and Hilton (2011) indicates that most studies of simulations have focused on conceptual understanding, providing promising evidence that simulations can advance this science-learning goal. The review shows moderate evidence that simulations motivate students' interest in science, and even less evidence about whether they support other science-learning goals (science process skills, understanding of the nature of science, scientific discourse and argumentation, and identification with science). Furthermore, a third review made by Rutten et al. (2012) provides evidence that simulations can enhance traditional instruction, but it also highlights that aspects such as teacher support and specific learning scenarios play an important role that has not been usually taken into account. In fact, beyond the technical features of simulations for science instruction, their educational impact cannot be separated from the pedagogical approach given by teachers (Hennessy et al., 2007; Pintó & Gutierrez, 2004).

Most of educational simulations used in schools have been designed by teachers, specialists from universities, publishing companies, or other educational institutions, trying to bring scientific concepts to students in the most comprehensible way as possible. In fact, behind the development and the promotion of these visual tools, there is the underlying idea that visualisation is a powerful tool for science teaching and learning, since the power of visual representations is actually based on the visual nature of science itself (Lemke, 1998; Norris, 2012; Phillips, Norris, & Macnab, 2010). For these reasons, simulations usually include several visual resources such as richness of colour, depictions of representations of invisible and abstract entities, multiple representations combining realistic, and abstract and mathematic representations. And the digital nature of these representations also allows interactivity features (such as draggable objects, scroll bars, buttons, and control items), dynamism, or 3D representations. Beyond the discussion about the suitability of including these visual elements, that is the instructional design factors and principles proposed by Cook (2006) or Plass, Homer, and Hayward (2009), we are especially interested about the 'reading process' that takes place when any student interacts with any simulation depicted on a computer screen in an instructional context: the wide variety of perceptive and cognitive mechanisms that can affect the interpretation of these visual representations and hinder student understanding of depicted content. In other words, despite the well-meant desire of most of simulation designers for creating easily comprehensible and communicative visual instructional materials, students' understanding of these depicted visual representations cannot be given for granted. For this reason, we will have to focus on the visual reading process.

Students' reading of scientific visual representations depicted on simulations

Reading visual representations as a semiotic process

What does 'reading' a visual representation exactly mean? Leaving the artistic issues aside, when a student reads a visual representation depicted on a computer screen, different processes take place. The reader needs to identify all the visual elements and the most important features, decode the visual grammar of the depicted representations, relate it to their meaning, and construct the conveyed message. Despite the absence of a unified framework for analysing students' reading difficulties, an interesting starting point was proposed by the set of studies by the STISS project, which are summarised in Pintó and Ametller (2002). Taking advantage of the semiotic framework proposed by Kress and van Leeuwen (1996) or Martin and Veel (1998), different studies from the science education perspective analysed student difficulties when reading static visual representations on energy (Ametller & Pintó, 2002; Stylianidou & Ogborn, 2002), optics (Colin, Chauvet, & Viennot, 2002), and kinematics (Testa, Monroy, & Sassi, 2002). One of main identified students' reading difficulty was the problem that arose when students had to understand the compositional structure of the depicted images – that is, the visual arrangement of the different elements of the composition. Thus, students experienced difficulties to understand the syntactic arrangement and relationship between the different visual elements, such as the left–right or top–down arrangement (Veel, 1998), the use of connectors such as arrows (Ametller & Pintó, 2002), the framing of elements into groups and subgroups (Stylianidou & Ogborn, 2002), among others. In these findings, the lack of students' knowledge of the visual language (which was defined as the 'visual grammar') was identified as one of the main reasons for reading difficulties. Nevertheless, these difficulties were not only related with this lack of visual skills, but also to the students' previous scientific knowledge in the domain, which in turn is influenced by the wide range of students' alternative conceptions about each of the depicted scientific concept (Driver, Squires, Rushworth, & Wood-Robinson, 1994; Gunstone, 1989). In other words, difficulties concerned not only the syntactic level, but the semantic level and the way students linked signifier and signified (Ametller, 2009). A clear example of these semantic difficulties is the synonymy, homonymy and/or polysemy of symbols (Ametller & Pintó, 2002).

Another students' difficulty identified in these previous researches is related with the relevance that students gave to the different visual elements displayed in the representations. Ametller and Pintó (2002) found that students did not select certain elements to be highlighted, often in relation to textual/graphical features which made them salient or not. Testa et al. (2002) found a 'Gestalt' influence that triggered misinterpretations where the shape seen was linked to contents that are inappropriate for the represented situation. In fact, a similar result had also been identified by Jiménez (1998) concerning the 'strong and weak shapes', when he realised that students interpreted wrongly the rotation axis of the coil of Figure 1, because of the precedence of the shape of the magnet.

These kinds of students' difficulties bring us to the idea that students can give more relevance to some visual elements than others, which hinder the understanding of the full composition. Indeed, the difficulties that can arise during the reading of a visual representation cannot be only explained by the semiotic framework, but also by the perceptive and cognitive process beyond the reading of a visual representation.

Reading visual representations as a perceptive and cognitive process

Any reading process can be understood by a cognitive process affected by the representational connections that each reader is able to make in his memory (Schnotz, 2005). In

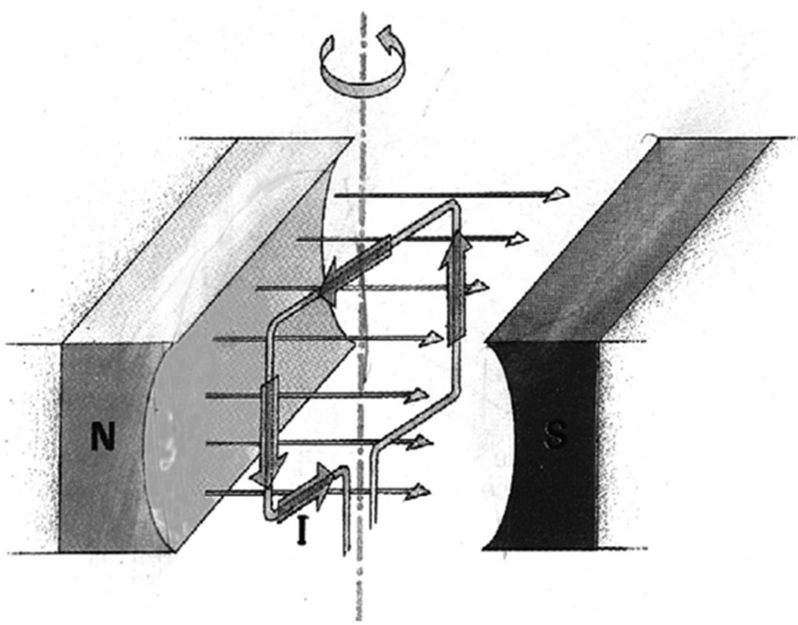

Figure 1. Representation of a one-loop coil turning inside a magnetic field (Jiménez, 1998).

this sense, the relevance that students give to each visual element can be explained by the idea of precedence of global features in visual perception theory defined by Navon (1977). According to Winn (1994), factors that affect these relevance are the contrast between the figures and the background, the simplicity, the thickness of the stroke or symmetry, and another factor that modulates the perception is attention, which is highly influenced by the goals of reading (Kulhavy, Lee, & Caterino, 1985). Lowe (2003), however, argues that the reader's attention of a visual element is more affected by its perceptual salience than by its thematic relevance. Overall, it can be stayed that students do not always focus their attention in the same sense that image designers should expect. More in detail, Cook, Wiebe, and Carter (2008) found that the reading difficulties arose when students had to split their visual attention between different parts of the representation, especially those students with a low prior knowledge. So, moving on to other aspects of the reading process that takes places when students visualise depicted images in science instruction, it is necessary to take into account what happens when students split their attention into different sources of information. This question has been widely discussed through the idea of multiple representations (Ainsworth, 1999, 2006), despite this definition does not only concerns the elements integrating a visual composition, but a broader idea of combination of information (images, text, gestures, sound, etc.). According to Ainsworth (2006), students can take advantage of the existence of multiple sources of information, but they are faced to new cognitive tasks in order to understand them, what brings to a new typology of students' reading difficulties related with the way that students split the attention between representations or the way they connect the different information. These questions have also arisen in the field of science education – in physics (Meltzer, 2007), chemistry (Treagust & Gilbert, 2009), biology (Treagust & Tsui, 2013), or nanoscience (Tang, Delgado, & Moje, 2014). For the specific case of scientific simulations, O'Keefe, Letourneau, Homer, Schwartz, and Plass (2014) have recently compared the transitions that students make between multiple representations in an educational simulation (in this case, including the representation of the particles of an ideal gas, a mathematical graph of V(T) or V(P), and control sliders), which usually depends on learning outcomes, and also that the efficacy of these simulations for learning depends on users' ability to integrate multiple sources of information.

Furthermore, we must say that most of the previously presented research expressed concerns over the visualisation of static images (either simple or multiple) and, for this reason, a new approach must be included in order to address students' difficulties when visualising simulations. Because of their interactive nature simulations hardly ever include dynamic representations and, besides, they usually include multiple dynamic representations (Ainsworth & van Labeke, 2004; van der Meij & de Jong, 2006). That is, simulations include moving objects, appearing and disappearing of objects, changing of the shape or the colour, plotting graphs, among others (Lowe, 2003). Several investigations have analysed the impact of this dynamism in students' comprehension of simulations. The 26 primary studies' review made by Höffler and Leutner (2007) states an instructional advantage of animation over static images, especially when animations are representational rather than decorative. Nevertheless, misinterpretations can still be accentuated due to the constraints imposed by learners' limited sensitivity to incoming dynamic information (Meyer, Rasch, & Schnotz, 2010), and also because of the students' tendency of extract the most perceptual salience animated information instead of the most relevant information. In addition, Lowe (2003) found that those animations that present very specialised dynamic subject matter having a high degree of visual complexity may actually have negative consequences for learners who are novices in the depicted domain. Finally, the combination of this positive and negative effect of dynamism in students understanding led Tversky, Morrison, and Betrancourt (2002) to state that, once again, it is not appropriate to ask whether animations assist learning, but under what conditions can help animations improve learning.

Overall, taking into account the previously reported students' difficulties when reading static representations, we should envision that similar reading difficulties also arise when students read the dynamic representations depicted in scientific simulations. Furthermore, we assume that these reading difficulties can hinder students' interpretation of the information that the designers of the simulation expect to communicate. For these reasons, we expect to identify the specific reading difficulties appearing when secondary-school students visualise two physics' simulations, in order to develop a deeper understanding of students' reading process that take place in simulation-based science instruction, and also in order to help secondary-school science teachers to optimally plan their simulation-based instruction, foreseeing these difficulties and addressing them with appropriate scaffolding.

Research questions, design, and methods

The study reported here addresses the following questions:

(a) How do students read secondary-school physics simulations and which difficulties arise during the reading process?
(b) How can these difficulties be classified based on its nature, for preventing them in teaching and learning contexts?

To answer these questions, we first selected two simulations, and then we interviewed a set of students while they were visualising these two simulations. Afterwards we analysed these interviews, identifying and classifying their difficulties as described below.

Selection and analysis of simulations

The two computer simulations were obtained from PhET platform (http://phet.colorado.edu/), since it is one of the most relevant and worldwide known online simulations repositories (Wieman, Adams, Loeblein, & Perkins, 2010; Wieman et al., 2008), which has delivered more than 100 million simulations to students in the last 10 years and holds an international recognition through several scientific and educational awards. The first selected simulation is named 'Friction' (Figure 2), and it intends to communicate the relationship between friction and heating. This simulation includes a representation at a macroscopic level of interaction (at the left-side of the image there is a book on top of another) and the representation at the molecular level (at the right-side of the image there are two groups of particles vibrating and colliding following a molecular-kinetic model), accompanied by a thermometer. When students interact with this simulation – dragging one of the books' surfaces, the vibration rate of particles increases and, simultaneously, the temperature rises. Later on, if the surfaces remain still, particles' vibration

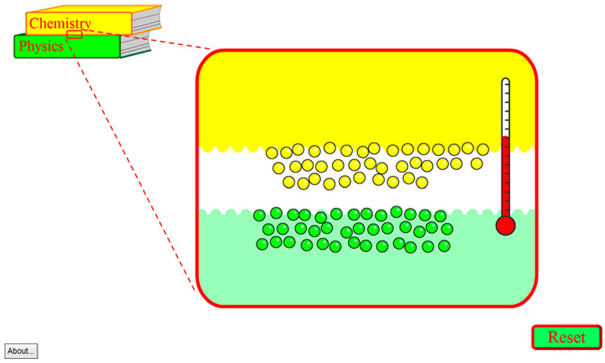

Figure 2. Simulation 'Friction'. It represents the relationship between friction and heating. It is available in: http://phet.colorado.edu/en/simulation/friction.

rate decrease and the temperature also decrease following an exponential cooling. Finally, if the friction is very hard, some particles break away, as a representation of the erosion that any surface experiences when it is rubbed.

The second simulation is named 'Faraday's Law' (Figure 3), and it intends to show a qualitative approach of the electromagnetic induction produced within the interaction between a coil and a magnet that can be dragged by students around the screen. When the magnet is moved around or inside the coil, some electric current is instantly produced. To represent this electric current, the bulb lights and, simultaneously, the needle inside the voltmeter moves to the positive and the negative markers. This simulation allows students to observe the representation of the magnetic field lines, and also to switch the orientation of the magnet.

For simplicity, these two simulations 'Friction' and 'Faraday's Law' will be hereinafter referred to as simulations A and B.

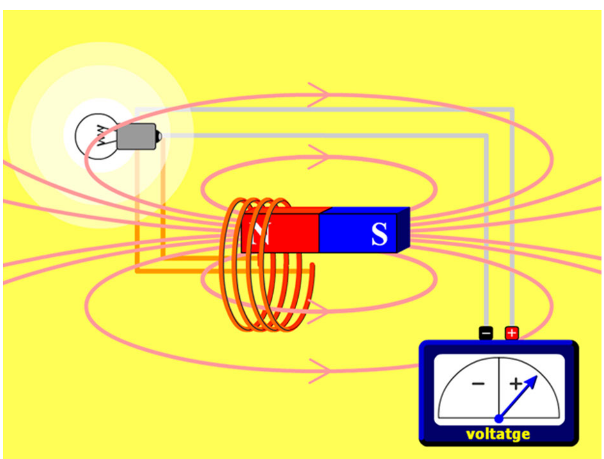

Figure 3. Simulation 'Faradays' Law'. It represents the electromagnetic induction (Faraday's Law). It is available in: http://phet.colorado.edu/en/simulation/faradays-law.

Development and analysis of students' interviews

For each of the two simulations, a group of 9 students aged 14–16 from 6 different secondary schools were selected. They were selected in collaboration with their respective physics teachers, following the criterion of being talkative students. All students had some prior knowledge about the scientific topics depicted on their corresponding simulation, but none of them was an expert on the domain. For each student, an individual semi-structured interview was carried on, where students were asked to carry out two main tasks: First, they were asked to describe the visual representation depicted in the simulation, following the statement 'Imagine your friend is next to you with his/her eyes closed. Try to describe him/her all what you see, including as details as possible'. Later on, students were asked to explain the scientific meaning of the depicted representations, following the statement 'Imagine your friend does not know about this scientific topic. Try to explain to him/her what the simulation is trying to tell you?' Each interview took about 20 minutes, including specific questions to those elements (both visual and conceptual) that had not been directly mentioned by students. All the interviews were video-recorded and transcribed. We used the numbered codes from A1 to A9 to refer to the nine students who were interviewed with simulation A 'Friction', and the codes from B1 to B9 to refer to the nine students who were interviewed with simulation B 'Faraday's Law'.

Later on, we divided each interview into an average between 10 and 15 thematic fragments, depending on each student. For example, interview to student [A1] was divided into 12 fragments, coded as following:

- A1-Fragment 1: General description of the simulation A.
- A1- Fragment 2: Discussion about the relationship between the two books and the particles.
- A1- Fragment 3: Description of the movement of the two books.
- A1- Fragment 4: Description of the behaviour of the particles.
- A1- Fragment 5: Description of the shape defined by the contour of the particles
- A1- Fragment 6: Explanation about the shape defined by the contour of the particles
- A1- Fragment 7: Description of the rate of decrease of temperature.
- A1- Fragment 8: Discussion about the relationship between friction and increase of temperature.
- A1- Fragment 9: Explanation of increase of temperature in terms of particle collisions.
- A1- Fragment 10: Recapitulation and new explanation about the position and the behaviour of the particles.
- A1- Fragment 11: Recapitulation and new discussion about the compositional structure of the simulation (the depicted zoom).
- A1- Fragment 12: Elaboration of summary and conclusions.

For each fragment, students' explanations and comments were analysed in order to identify which reading difficulties could be involved. During this process, a list of reading difficulties resulted into a classification system with a wide range of categories and subcategories, taking advantage of a qualitative data software Atlas.ti.

Analysis of students' difficulties in reading visual representations

Through the classification of identified students' answers from the point of view of which difficulties can be involved, five main categories were defined: difficulties in the reading of the compositional structure of the representation (CS), difficulties to give appropriate relevance to each visual element in the composition (RE), difficulties to give appropriate semantic meaning to each visual element in the composition (SEM), difficulties to deal with multiple representations (MR), and difficulties to perceive and interpret dynamic information (DY). For each case, a set of subcategories were defined too, which were coded using the suffixes 1, 2, 3, etc. Followingly, we present these categories and subcategories that resulted from the analysis, including some examples of the quotes of students' interviews in italics, followed by the code for its corresponding student in square brackets.

Difficulties in the reading of the compositional structure of the representation (CS)

The analysis of some students' answers suggests that during the visualisation of the simulations, students can misread the spatial arrangement of the different visual elements – that is, the syntactic relationship between them, giving them a different meaning than the expected one. According to the nature of the spatial arrangement of the visual elements of a simulation, these students' difficulties have been classified into two subcategories. First, students can misread the relationship between different visual elements of the composition which are placed next to each other in the two dimensions plane of the screen (CS1). Second, students can misread the relationship between different visual elements of the composition which are overlapped in different layers (CS2).

For the case of simulation 'Friction', some students experienced CS1 difficulties when trying to understand the left–right arrangement of the visual elements – that is, when trying to understand the compositional structure that corresponds to a 'zoom-based relationship' between the left-side of the composition (the macroscopic representation of the books) and the right-side of the composition (the molecular representation of the contact-surfaces between the books), as depicted in Figure 4. According to Kress and van Leeuwen (1996), this kind of compositional structure can be considered an analytical structure that relates the part with the whole. Instead of reading this zoom-based relationship, some students related the verbal labels 'physics' and 'chemistry' with the particle representations, understanding the compositional structure as it were a 'label-based relationship' (Figure 5). For example, student [A1] expressed 'in the simulation there are physics atoms and chemistry atoms', and later she said 'there is an arrow that connect the physics with the green balls'. That is, she was reading the compositional structure as an analytical structure, but as a *classificacional* structure (Kress & van Leeuwen, 1996). Other difficulties classified as CS2 were the difficulty for understanding the overlapping between the particles and the background represented behind them.

Difficulties for understanding the compositional structure of the representation were also identified for simulation 'Faraday's Law', both for CS1 and CS2. In fact, the compositional structure of this representation should be understood as a circuit-based structure, where the different elements are connected by electrical wires (Figure 6). Some students did not notice these wires, and they made alternative explanations in terms of the

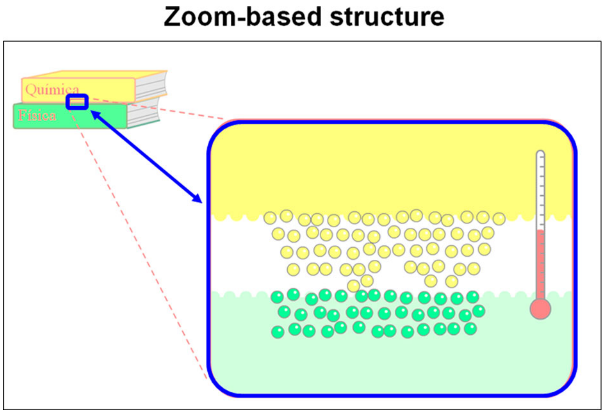

Figure 4. Compositional structure that represents the 'zoom-based' relationship between the left-side and the right-side of the visual representation.

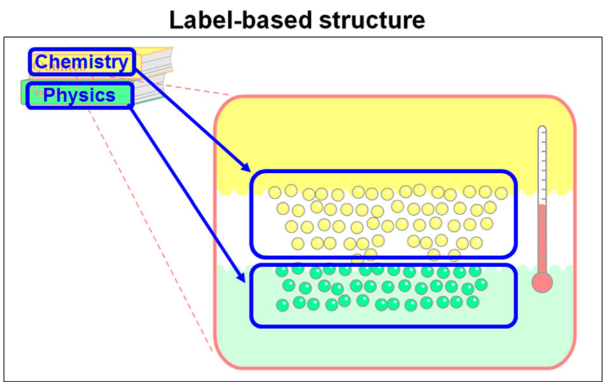

Figure 5. Misunderstanding of the compositional structure based on a 'label-based' relationship between the left-side and the right-side of the visual representation.

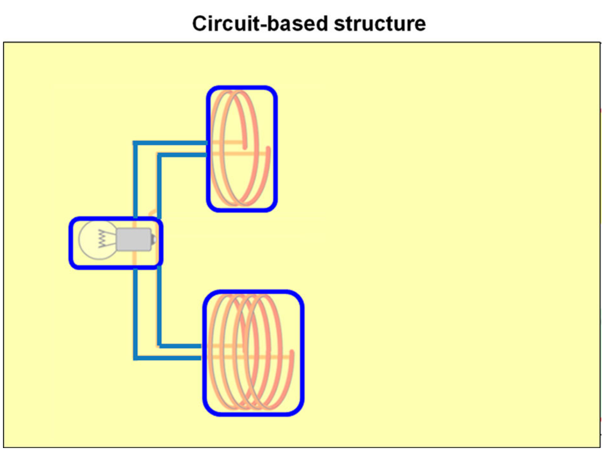

Figure 6. 'Circuit-based' compositional structure, where the different elements are connected by the wires.

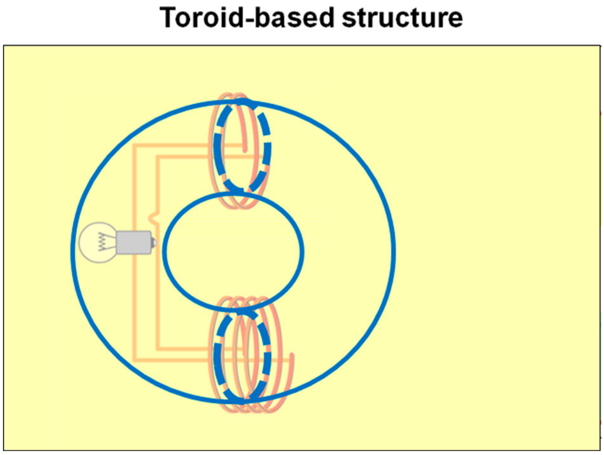

Figure 7. 'Toroid-based' compositional structure, where the two coils correspond to the highest and the lowest parts of an imaginary toroid drawn by student A8 imagination.

correspondence circuit elements, such as 'there are two coils because there should be two bulbs and two magnets too' [B2]. Other alternative explanations concerning the compositional structure can also be observed in student [A8], who stayed that 'The objective is to move the magnet drawing circles', and then he began to drag the magnet moving it in circle (see Figure 7) as if the two coils corresponded to a toroid-based structure. For this student, the two coils did not correspond to pieces of an electric circuit, but to the highest and the lowest parts of an imaginary toroid drawn by his imagination, within which the magnet should be moved making loops.

Difficulties in giving appropriate relevance to each visual element in the composition (RE)

When the students participating in our research were asked to describe the visual elements displayed on the simulation, it could be observed that some students gave a wrong relevance to some of these elements, in some cases highlighting them in excess and in other cases omitting them. As stated in the previously presented framework, students tend to give more attention to the more salient elements depending on its position, its simplicity, the thickness of its stroke, its symmetry, among others; but its relevance is also affected by the goals of the reading embedded in a sociocultural context. According to the answers given by our participants, different kinds of difficulties related to the relevance that students give to each visual element of the composition were identified, and then have divided them into four types: related with the relevance of the colour of visual elements (RE1), their shape (RE2), their position in the composition (RE3), and finally the relevance given to the embedded verbal labels (RE4).

Concerning simulation 'Friction', different kinds of RE2, RE3, and RE4 were identified. First, for RE2, it was identified that students did not notice about the irregular arrangement of the particles, which tries to represent how flat macroscopic surfaces are actually rough at a mesoscopic level. For RE3, it was identified that some students gave an over-relevance to the visual elements sited in the centre of the composition while they did not take into account the books depicted in the left corner of the representation. For instance, student [A2] began her description of the image by giving details about the behaviour of the particles, but she did not include any explanation about the micro-macro relationship. Later, when she was asked about it, she answered 'Oh, the books! I hadn't seen these books before!' (Figure 8). Finally, for RE4, it was identified that some students highlighted the verbal labels of 'Physics' and 'Chemistry' in excess, which even led to student [A1] to say that 'it is a chemical reaction' .

In the case of the 'Faraday's Law' stimulation, RE1, RE2, and RE4 were also identified. Student [B3], for instance, over-emphasised the blue and red colours of the magnet as if it was very relevant information (RE1), and [B1] did not realise that letters 'N' and 'S' corresponded to 'North' and 'South', respectively. Nevertheless, we identified a reading difficulty to which we want to pay more attention, and it concerns the relevance that students gave to the cylindrical shape of the coil. More specifically, we observed that students gave precedence to the idea of a hollow cylinder (that is, with a 'hole' in the middle) rather than a continuous line (that is, a spiral wire), and then they said that it corresponded to a 'gap' in the circuit: 'The circuit is open because there is a gap in the middle. When I introduce the magnet, the circuit becomes closed, and electric current can flow through the circuit' [B6]. Actually, according to the precedence of global features in visual perception theory (Navon, 1977), we can assume that the global feature of the coil is the 'hollow cylinder' shape, while the local feature is a 'continuous line' shape, and thus the explanation by these can be understood (Figure 9).

Difficulties in giving appropriate semantic meaning to each visual element in the composition (SEM)

Apart from how students understand the compositional structure, and the relevance they give to each visual element, some identified difficulties in the reading process concerned the meaning that they gave to each element of the composition. For this reason, we considered them as reading difficulties concerning the semantic level. Since most of depicted visual elements correspond to scientific objects (whether real devices or abstract entities),

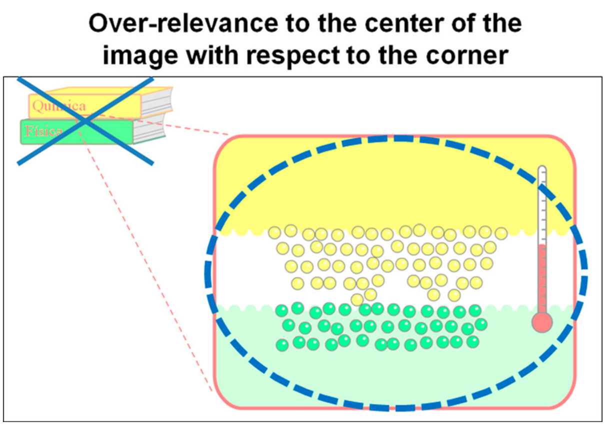

Figure 8. Over-relevance of the central elements of the composition in contrast with the under-relevance of the elements of the left-side.

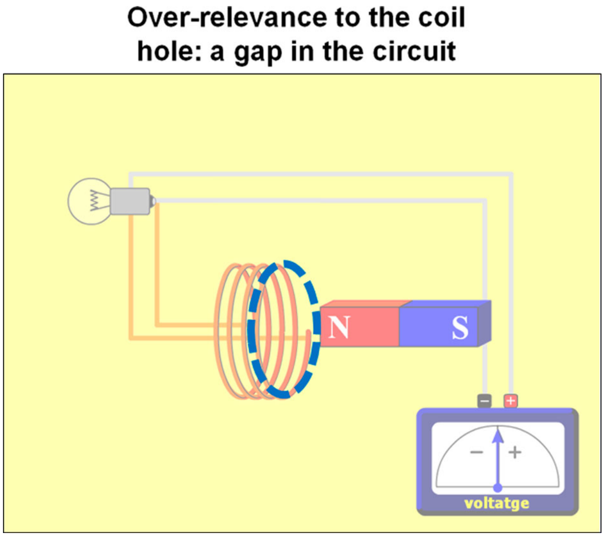

Figure 9. Cylindrical shape of the coil is understood by some students as a 'gap' in the circuit that does not allow the electric current to flow. According to students' answers, if the magnet gets inside the coil, then electric current can flow.

this meaning given by students will be strongly influenced by their previous knowledge. According to the answers given by some students, these reading difficulties at the semantic level include situations where the meaning that students give to an element of the composition correspond to the meaning of another representation that looks similar (SEM1). In previous studies, this confusion of the meaning has been defined as homonymy. Similarly, semantic difficulties also include those situations where students express a lack of previous knowledge that does not enable them to give an appropriate scientific meaning (SEM2). When this occurs, some students simply express their lack of knowledge with expressions such as 'I don't know what it means', and some other times they take advantage of their inventiveness and creativity to give alternative meanings to these visual elements.

For SEM1, this visual similarity between elements of the representation and other representations related to the previous knowledge of the students was expressed by students when explaining the meaning of the particles in the 'Friction' simulation (A). Some explanations included terms such as 'melting' [A6] or 'It turns from solid to liquid' [A9] to describe the behaviour of the particles when they increased the vibration rate. In fact, in Figure 10, a visual similarity can be observed between the particles' representation of the simulation and the typical particles representation used in schools to explain the molecular-kinetic model. Something similar was observed in answers concerning the 'Faraday's Law' simulation (B). Student [B4] referred to the voltmeter as 'There is a machine that detects the force of the magnet', and then she tried to describe the voltmeter's needle in terms of the poles of the magnet, which made us suspect that she was thinking more in terms of a compass than an actual visual similarity with the voltmeter (Figure 11). So, in both cases (Figures 10 and 11), very similar graphical characteristics can be observed, according to the idea of homonymy proposed by Pintó and Ametller (2002), which led students to infer a parallelism between representations.

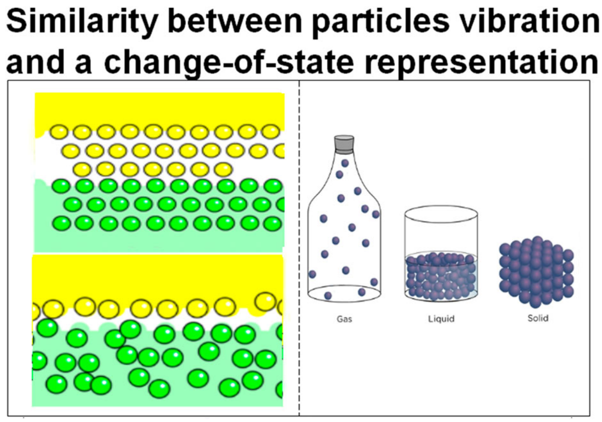

Figure 10. The visual similarity between the particles and a typical particles representation used in schools to explain the molecular-kinetic model.

Different difficulties for SEM2 have also been identified. For simulation A, some students stated that they did not know the meaning of the particles breaking away (that is, the erosion of the material), and for simulation B, some students noted not to know the meaning of the voltmeter or the magnetic lines. In some cases, students gave inventive alternative answers, such that voltmeter was 'a machine that regulates the electric current to avoid the explosion of the bulb' [B2].

Difficulties in dealing with multiple representations (MR)

Another kind of students' difficulty concerned the integration of information coming from different visual elements (that is, different sources of information), which had previously been defined as multiple representations. We considered the kinds of difficulties in those cases where students did not correctly relate these multiple pieces of information

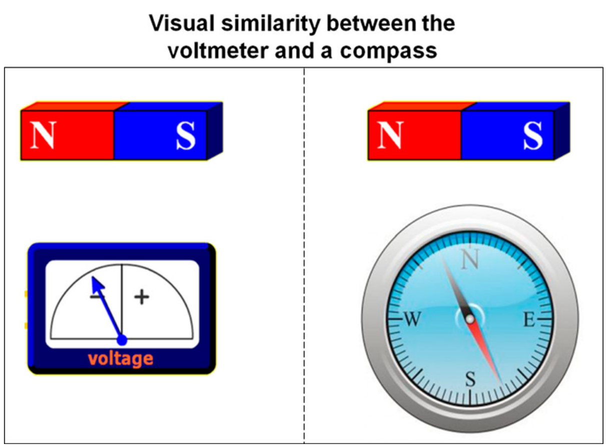

Figure 11. The visual similarity between the voltmeter and the compass, since both include a needle that moves.

(Ainsworth, 1999, 2006; Ainsworth & van Labeke, 2004). According to the nature of the depicted information, the difficulties concern the integration of two pieces of redundant information (MR1); the wrong combination of two pieces of complementary information (MR2); and finally, the lack of discrimination of two pieces of different information (MR3).

In the 'Friction' simulation (A), the difficulties in integrating two redundant pieces of information (MR1) arose when some students had to combine the two representations concerning the idea of the matter that composes the surface of the two books: the particle-based representation of matter and the continuous-based representation of matter, which is depicted by the coloured background behind the particles (Figure 12). When some students tried to explain the nature of these two representations, they provide alternative explanations. For example, student [A6] proposed that the coloured background corresponds to a 'membrane where particles are embedded', and student [A3] said that 'the small balls are the atoms, and the background corresponds to the other particles'. In this same simulation, the difficulty in integrating two complementary pieces of information (MR2) arose when students had to relate the behaviour of the particles and that of the thermometer (Figure 13). In fact, this particles–thermometer integration is the basis for one of the main ideas of the simulation: temperature corresponds to the average velocity of the random motions of microscopic particles. Nevertheless, some students were not able to relate both representations. This was identified by statements such as 'I don't know what has to do the particles and the thermometer'. Finally, other students were not able to discriminate two different representations (MR3) corresponding to the particles that vibrate (but remain in the same position), representing the temperature, and the particles breaking away, representing the erosion of the material. In other words, despite that the simulation tries to communicate that the friction of two surfaces implies two consequences (both the heating and the erosion of the surfaces), some students mixed both ideas.

As regards the 'Faraday's Law' simulation, different difficulties for integrating complementary representations also arose. The representation of the current in the circuit can be observed by the light of the bulb and by the movement of the voltmeter needle

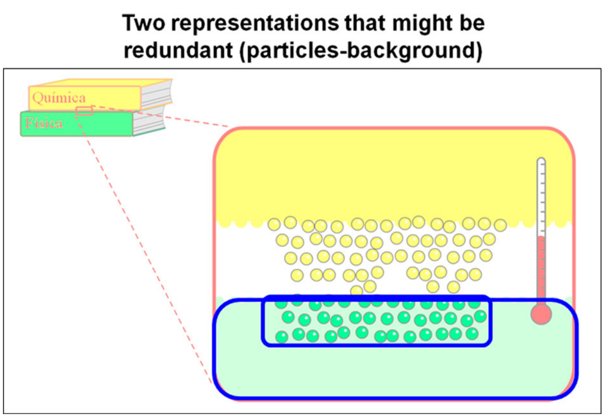

Figure 12. Two representations that might be redundant because both make reference to the idea of the matter that composes the book surfaces.

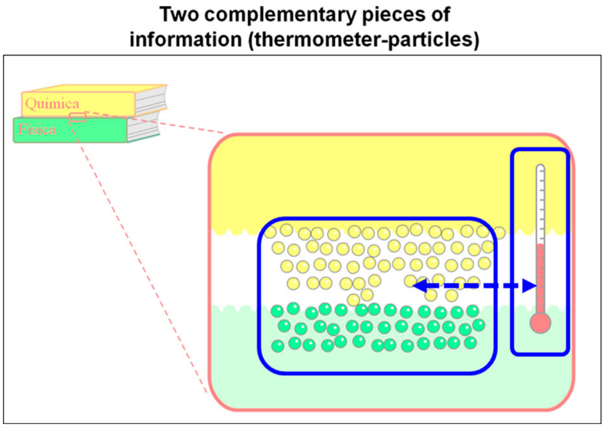

Figure 13. Two representations that might be complementary because their integration tries to communicate the idea that temperature corresponds to the average velocity of the random motions of microscopic particles.

(Figure 14). However, some students did not integrate both representations (MR2), as occurred with student [B1], who stated that 'the bulb only lights when the voltage is positive', despite the bulb actually being lit while the voltage was also negative. That is, student [B1] seemed not to be able to combine the complementary information depicted in the representation. In addition, other students combined representations without any apparent relationship (MR3). This is the case of student [B9], who directly related the bulb lighting with one of the magnetic lines, considering that these light up because of the interaction between the magnetic line and the bulb (Figure 15): 'the bulb lights when it enters inside the magnetic field'. It is important to mention that when asked about what 'inside the magnetic field' meant, he answered that he was referring to the area

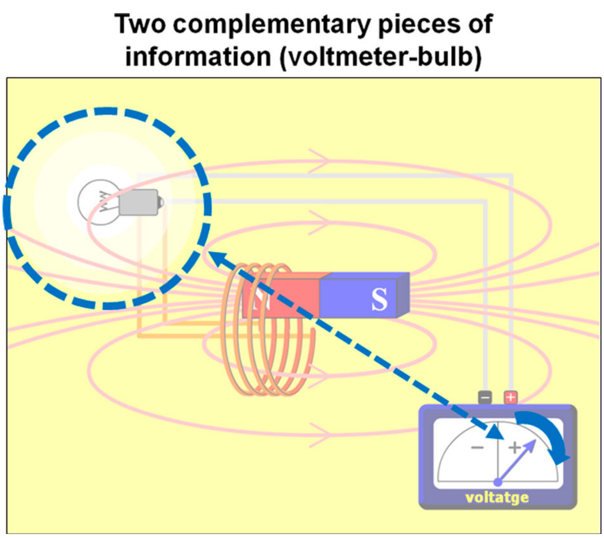

Figure 14. One of the main requirements to read and to understand the simulation is to combine the information obtained from the bulb and from the voltmeter.

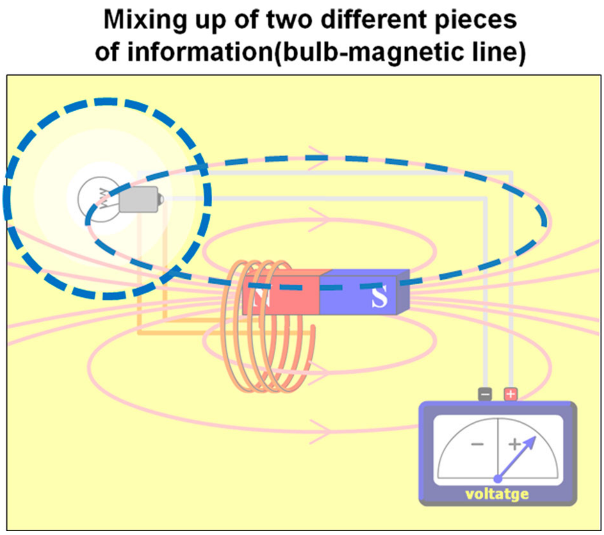

Figure 15. When the magnet crosses the coil, coincidentally, one of the magnetic lines passes over the bulb. Student B9 assigns causality between both representations.

defined by the magnetic line. So, instead of relating the magnetic line with the coil, student [B9] directly related the magnetic line with the bulb.

Difficulties in perceiving and interpreting dynamic information (DY)

The last type of difficulties identified from the students' answers concerns the reading of information depicted by the dynamic elements of the simulation. Some students did not correctly perceive and understand the dynamic information displayed in both simulations, whether translations, transitions, or transformations (Lowe, 2003). First, we identified the confusion between the position-dependence behaviour and the movement-dependence behaviour (DY1). Furthermore, we also identified the confusion between simultaneous and successive represented processes (DY2). Another defined subcategory included the perception of the non-linear changes as if they were linear changes (DY3), and finally, we identified the lack of perception of the intensity of a dynamic representation (DY4).

As regards the confusion between the position-dependence behaviour and the movement-dependence behaviour (category DY1), two similar results were found in some students' answers about both simulations. In the 'Friction' simulation (A), some students said that the two surfaces were heated because of the contact position, and not because of the friction movement. This occurred, for instance, in student [A1], who said that 'when we join the books they are heated' and then 'when we separate the books, they are cooled' (Figure 16). At the same time, in the 'Faraday's Law' simulation (B), some students understood that the electric current was generated because of the contact between the coil and the magnet, and not because of the movement (and the velocity) of the magnet. Once again, we saw explanations such as 'the electricity depends on the position of the magnet' [B4], without any reference to its movement (Figure 17).

Other difficulties have also been identified regarding the confusion between simultaneous and successive represented processes (DY2), as occurs in simulation B with the

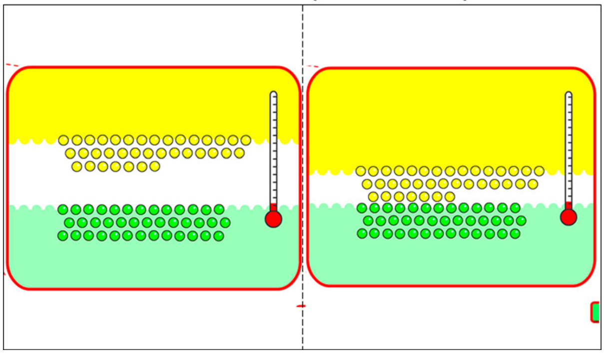

Figure 16. The contact (and not the relative movement) of the books is understood as the cause of the heating.

dynamic representations of the bulb (lighting) and the voltmeter (needle switching). Statements by the students such as, 'first the current pass through the voltmeter, and then the bulb lights' shows this confusion, and show the existence of successive reasoning in the students' answers (Viennot, 1996). The perception of the non-linear changes as if they were linear changes (DY3) was observed for simulation A, as regards the dynamic behaviour of the thermometer. In this sense, most of interviewed students described the decreasing rate of the temperature as linear. For example, student A5 said that 'temperature drops down at a constant rate', that is, she did not perceive how the temperature decreases faster during the first moments and then gets slower (Figure 18).

Finally, the lack of perception of the intensity of a dynamic representation (DY4) was also identified in answers concerning both simulations. In simulation A, the intensity of the vibration of the particles changes along the time, since it increases suddenly when friction is produced, and later on it decreases gradually. However, the two groups of particles have the same behaviour. However, we realised that when student A7 was talking about this vibration, he stated that 'green particles move faster than yellow particles', and then he tried to explain it was because of the forces involved in the phenomena. In simulation B, we realised that some students only explained the illumination of the bulb in terms of 'it is lighted' and 'it is not lighted', but without any reference of the different levels of the intensity of its light. Even student B7 said that 'the bulb always lights in the same way', so he did not realise how more wires or more magnet velocity can induce more or less electric current.

Summary and discussion of the results

The ensemble of episodes where reading difficulties were identified across the 18 conducted interviews is summarised in Table 1. The two columns on the left include all the categories and subcategories previously defined and exemplified. The columns on the right represent the seven students who read simulation A (A1–A9) and the seven students who read simulation B (B1–B9). The black point (•) represents an episode where a specific difficulty has been identified in a student's interview, including the previously reported examples, as well as other similar episodes. In the table, when two points coincide in

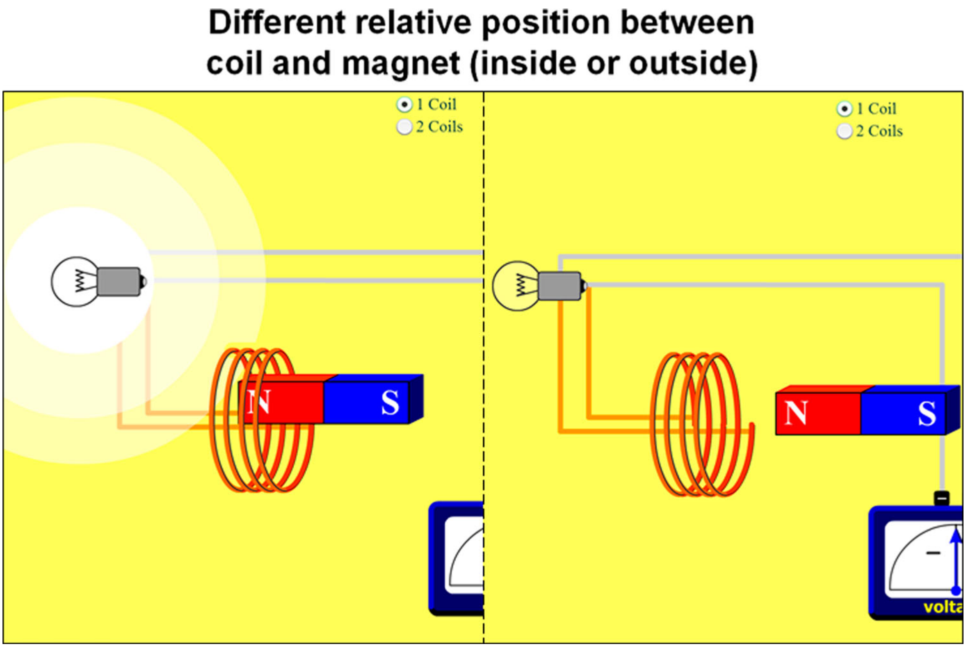

Figure 17. The contact (and not the relative movement) between the magnet and the coil is understood as the cause of the electric current.

one box (••), it signifies that two different difficulties concerning the same category have been identified in the same student in two separate episodes.

The wide range of reading difficulties identified through the 18 interviews has allowed us to define categories concerning very varied aspects of the visual features of the representations. Assuming the frame of 'visual grammar' proposed by previous works (Kress & van Leeuwen, 1996; Pintó & Ametller, 2002), it is then possible to assume the different linguistic levels in which students' difficulties can be situated. Thus, there would be a syntactic level closely related to what we have defined as compositional structure (CS), which

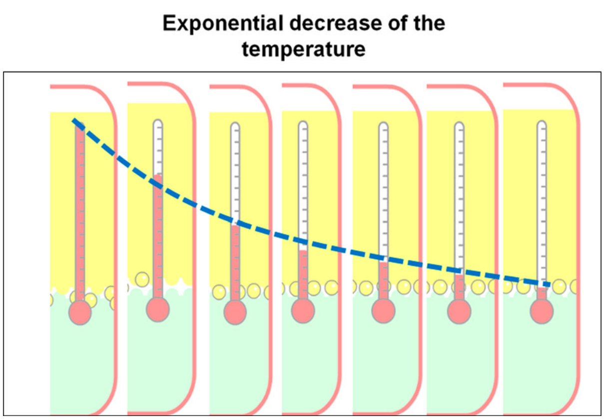

Figure 18. The rate at which temperature decreases according to the thermometer corresponds to an exponential decay.

Table 1. Rows represent categories of reading difficulties.

		A1	A2	A3	A4	A5	A6	A7	A8	A9	B1	B2	B3	B4	B5	B6	B7	B8	B9
CS	CS1	•		•				•		•	•	•	•	•	•			•	
	CS2	•					•	•					•						
RE	RE1												•				•		
	RE2	•	•	•	•	•	•	•			•	•	•			•			
	RE3	•	•					•											
	RE4	•		•			•				•	•							
SEM	SEM1				• •				•	•		•	•	•			•		
	SEM2	•		•		•	•	•	•			•				•		•	•
MR	MR1			•			• •	•											
	MR2	•	•			•	•		•		•	• •	• •	•					
	MR3	•		•	•	•	•							•					•
DY	DY1	•	•		•		•	•		•	•		•	•		•			•
	DY2											•	•						
	DY3	•	•	•	•	•	•												
	DY4				•			•				•					• •		

Note: Columns represent students (grouped into those who read simulation A and B, respectively).

includes aspects such as the arrangement, the grouping, and the connection between visual elements; and then a semantic level (SEM) associated with the meaning that readers give to these visual elements. Under this assumption, the question that arises is: whether other grammar levels could have been included in the analysis, especially the pragmatic level (that is, the ways in which context contributes to meaning). In this sense, it must be said that some identified difficulties could had been considered through this perspective. For example, in the 'Friction' simulation (A), particles include white points that represent the brightness (Figure 19), and despite that this is a decorative visual element, student [A6] gave a scientific explanation for it, stating that these points were 'the nucleus of the atoms'. Nevertheless, because of the highly contextual nature of the pragmatic level of grammar, and also because of a shortage of relevant data, an in-depth analysis into this kind of reading difficulties has been discarded in this paper.

Considering the sum of difficulties encountered during the interviews (summarised in Table 1), it can be observed that all students have experienced at least one reading difficulty, and that 16 of 18 students encountered three or more reading difficulties that correspond to three or more categories CS, RE, SEM, MR, or DY. This result shows that the difficulties that each student meets during his/her reading do not correspond to the same typology, but they are varied. In other words, we cannot only say that the variety of difficulties previously discussed is because of the variety of students, but also that most of the individual students experience a variety of difficulties. But at the same time, despite this variety, many similarities can be observed between the difficulties concerning the two simulations. Considering the 15 different subcategories of difficulties defined and shown in Table 1, there are 10 cases where the difficulty has been identified in the reading of the 'Friction' and 'Faraday's Law' simulations (coincident), and we also included three typologies of difficulties that only affect the reading of simulation A and two typologies, which only affect the reading of simulation B (non-coincident).

In the case of non-coincident difficulties that only occur in one of the two simulations, this is because of the very specific visual features of the representation, which do not have equivalence in the other simulation. For example, difficulty DY3, that is the perception of the non-linear changes as if they were linear changes, has been identified in six out of the eight students in the 'Friction' simulation (A), because of the exponential behaviour of the decrease in temperature, but it has not been identified in interviews concerning the 'Faraday's Law' simulation (B), since there is no exponential behaviour.

Focusing our attention in those difficulties that appeared in interviews concerning both A and B simulations, we must highlight the strong similarity found in some difficulties,

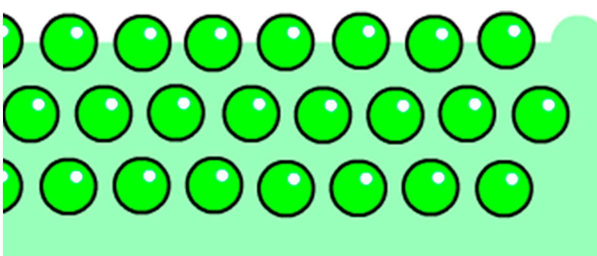

Figure 19. Each circle includes a small white point, which represents the brightness of naturalistic representations of the particles. It is decorative information.

despite the differences in the displayed content. For example, in both the A and B simulations, students confuse the position-dependence behaviour and the movement-dependence behaviour (category DY1). In simulation A, some students said that the two surfaces were heated 'because of the contact', and not because of the friction movement. At the same time, in simulation B, some students understood that the electric current is generated because of the contact between the coil and the magnet, and not because of the movement (and the velocity) of the magnet (see Figures 16 and 17). The coincidence of difficulties can be evidenced, for instance, in the wrong combination of two pieces of complementary information (MR2) that some students made, both for integrating the representation of the particles vibration and the representation of the thermometer (simulation A), and also for integrating the representation of the bulb and the representation of the voltmeter (simulation B). These and other coincidences lead us to believe that some of these difficulties could also be found in other physics simulations with similar visual features, according to the results of Pintó and Ametller (2002) about how common features of scientific images could be related to potential difficulties. In fact, as mention at the beginning of the paper, these features (interaction by dragging objects, multiple representations, etc.) are quite common in these kinds of educational tools.

Conclusions and implications

This variety of identified difficulties, their recurrence across the participants, and the coincidence found between the two simulations with a different scientific content emphasise that when secondary-school students read scientific visual representations, its canonic reading cannot be taken for granted.

First of all, students can misread the compositional structure of the representation, as stated by Ametller and Pintó (2002) or Stylianidou and Ogborn (2002), which has an effect on students' understanding of the whole composition. Despite this, misreading can not only lead to confusion by the student, but students might also give a completely alternative meaning to the spatial arrangement of its visual elements, conveying different information than that expected, as occurs with the interpretation of a 'label-based' structure of the 'Friction' simulation, and also with the 'toroid-based' structure of the 'Faraday's Law' simulation. Secondly, students can excessively highlight some visual elements, giving them too much relevance, but they can also give them too little relevance, to the extent that they may not even notice some elements of the composition, as occurs with the books displayed in the 'Friction' simulation. More specifically, some salient elements affect the reading. The shape of the coil of the 'Faraday's Law' simulation seems to be a 'strong shape' similar to the analysis of the results by Jiménez (1998) (Figure 1). Strong colours also can receive students over attention, which can be explained both by perceptive (Winn, 1994) and by a cultural factor (Kress & van Leeuwen, 2002). This cultural factor had also been identified in students' over-relevance to the embedded text (Stylianidou & Ogborn, 2002), as occurs with the decorative words 'Physics' and 'Chemistry' depicted in the 'Friction' simulation. In some cases, students' attention to these and other visual elements can even overshadow other visual elements, hindering the students' interpretation of the representation. If images include representation of scientific objects or entities which require some previous knowledge about the topic, students might have difficulties in giving them the appropriate meaning, and this difficulty can be enhanced if these visual elements have some visual similarities with other scientific representations already known by students. According to our findings, in both the 'Friction' and 'Faraday's Law' simulations, students introduced meanings to the depicted visual elements corresponding to previous science lessons, according to the students' spontaneous reasoning mechanism, defined by 'accessibility rule' (Pozo, Sanz, Gómez, & Limón, 1991). Similarly, as Ametller and Pintó (2002) had reported, students sometimes take advantage of their inventiveness for giving a meaning to the scientific depictions. All of these identified difficulties lead us to conclude that the meaning that students can give to the depicted information can strongly differ from the original meaning expected by simulation designers, which reinforces the idea that reading the depicted representation of a simulation does not always imply understanding its meaning.

Despite the affordances of simulation in terms of multiple and dynamic representations (Meltzer, 2007; O'Keefe et al., 2014; Tang et al., 2014), several difficulties in the reading by the students have also been identified. According to our findings, dealing with multiple complementary representations might be especially problematic in those cases where students should integrate different sources of information to achieve an actual understanding of the simulation content; since this integration should not be taken for granted, even if it might seem very 'obvious'. This is the case of the two selected simulations, both for particles–thermometer and for the bulb–voltmeter relationships. In these two cases, it can be shown that presenting these complementary representations does not automatically imply the integration of the depicted information. Furthermore, an extra challenge should be considered concerning the specificities for integrating macro- and micro-representations (Harrison & Treagust, 2002; Johnstone, 1991; Linjse, Licht, de Vos, & Waarlo, 1990), as occurs in the 'Friction' simulation, and also for integrating symbolic and real entities (Georges Olympou, Zacharia, and de Jong, 2012; Zacharia, 2007), as it occurs with magnetic lines in the 'Faraday's Law' simulation.

Additionally, the dynamic information depicted in simulations also offers several affordances in science instruction, which has generated a big debate about its impact on student comprehension (Meyer et al., 2010; Ryoo & Linn, 2012). In this debate, our findings indicate that students can find specific difficulties that hinder their interpretation of the depicted dynamic information, especially when students have to pay attention to a large amount of information (for example, to observe the movement of the magnet, the illumination of the bulb and the movement of the needle in the voltmeter, at the same time), and also when this information takes place in a short period of time (in both simulations, most of the depicted phenomena take less than a second). Furthermore, our results agree with the findings reported by Lowe (2003), which stated that the translation of visual elements (that is, the change in their position) can overshadow transitions (other changes).

Analysing some of the difficulties identified, a strong similarity with alternative conceptions identified in the literature can also be observed. This is the case of students statements about the particle vibrations in the 'Friction' simulation (Gustafson & Mahaffy, 2012), that particles are embedded in matter (Griffiths & Preston, 1992), but also about the electric current behaviour in the 'Faraday's Law' simulation, understood as successive (Driver et al., 1994; Shipstone, 1988), or that the bulb is illuminated only when the voltage is positive (Holton & Verma, 2011). Considering our results, we cannot say that these two simulations foster the alternative explanations given by the students, since it has not been possible to determine which of students' previous ideas were before visualising the simulations. Nevertheless, what we can state is that visualising the simulations does not automatically lead to students to overcome these alternative conceptions, contrary to the common assumption that simulations can help students to learn per se.

So, for an effective comprehension of depicted scientific content, students should overcome the different identified difficulties in order to benefit from the use of simulations. This implies that critical reading of images depicted in simulations should play a central role when using educational scientific simulations and other digital resources, including digital images (animations, games, virtual worlds, etc.). In fact, according to our results, we agree with Tversky et al. (2002) that we should not only ask if these kinds of digital resources actually assist learning, but under what conditions it can actually help students to learn. To address this problem, teachers should scaffold students' reading when they use computer simulations, and instructional materials should be also addressed for this specific purpose, especially in those cases where students have a low previous knowledge in the topic. For instance, teachers could ask students about the structure and the meaning of the representation, guiding step-by-step, if necessary (i.e. 'what do you see in this image?', 'what do you think this specific element means?'). However, in order to address, not only the syntactic and the semantic level, questions should also be focused in order to address the pragmatic level of the representation (i.e. 'why do you think that the simulation's authors decided to include this visual element in this image?'). In this sense, we agree with Shah and Hoeffner (2002) that graphical literacy skills should be taught in the context of science, and also that translating between representations may be beneficial (from visual to verbal languages), and also explicitly focusing on the links between visual features and the meaning. Finally, our conclusions also might imply that simulations should be carefully designed from the visual point of view, avoiding the overload of information, ambiguous information, and also those decorative elements and visual inaccuracies.

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