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How secondary school students conceptualize infrared radiation-matter interaction? Findings from a research study and implications for an instructional design

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Summary. — This study has been carried out within the REVIR scenario, which is a project promoting that secondary school students have access to a computerized laboratory at the Faculty of Education of our university and work in small groups during four hours with specific instructional material. One of the laboratory sessions included in the REVIR project deals with IR radiation-matter interaction, and is addressed to post-compulsory secondary students (16–18 year-old students). Within this framework, we have conducted a research study to analyse students' conceptualizations of the processes or mechanisms that take place in IR radiation-matter interaction (energy transfer, selective absorption), and its effects at a macroscopic level (temperature increase) and at a molecular level (vibration). For data collection, a question was posed to all students at the end of each REVIR session, asking students to relate what was described in an article about the application of an IR laser for acne treatment to what they had learnt throughout the session. The analysis of the 67 students' answers to that question revealed that many students explained the effects of the IR laser in vague terms, often repeating information included in the article, without explaining absorption of IR radiation in terms of energy. In consecutive versions of the instructional material, more oriented application questions were added after the article and explicit discussion around synthesis and exploratory (of students' previous ideas) questions was carried out during the session. From the analysis of 49 and 119 students' answers in consecutive later versions, we found that the introduction of these changes resulted in a greater number of students' descriptions in macroscopic and microscopic terms, and a lower number of answers simply repeating information extracted from the reading. Furthermore, more students explicitly explained absorption in terms of energy associated to IR light. Implications for the instructional design, in terms of critical features affecting people's abilities to transfer what they have learned, are discussed below.

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1. – Introduction

1˙1. *The research context: The REVIR scenario.* – This study has been carried out within a singular context, the REVIR (Reality-Virtuality) scenario. REVIR is a project giving access to secondary school students (12–18 years old) to a computerized laboratory at the Faculty of Education of our university. In each REVIR session, students work for four hours, most of the time in small groups (2–5 students), but they are also involved in whole group discussions. In each REVIR session, students use computers connected to an interactive whiteboard, but they also use other ICTs for collecting and analysing data, for visualization, etc. (data-logging systems, simulations, specific software, etc.), depending on the contents and experiments they perform.

In each REVIR session more than one teacher assistant is usually supporting and orienting students. Several REVIR sessions about different science topics are offered to schools at present, and they all include content from the official Catalan science syllabus. In each session, students are provided specific instructional materials in the form of digital worksheets describing the sequence of tasks to carry out and the questions to answer. The instructional materials for each session have been designed taking into account science education research findings (*i.e.* students' preconceptions and main difficulties on certain science topics, effective science teaching strategies, etc.). Furthermore, these teaching and learning materials are iteratively developed evaluating its effectiveness (*i.e.* the extent that the learning experiences and outcomes from the intervention are consistent with the intended learning objectives) and taking into account students' difficulties carrying out the tasks or answering the questions.

1˙2. *A REVIR session on IR radiation-matter interaction.* – One of the laboratory sessions included in the REVIR project deals with EM radiation-matter interaction, and is addressed to post-compulsory secondary school students (16–18 years-old). This topic has been recently included in the official science syllabus in Catalonia. Most teachers manifested a concern for how to deal with this topic in an experimental way. To attend this need, two of the authors designed a new instructional material to be offered as a new REVIR session. Its main aim is to make students understand the effects of infrared (IR) radiation-matter interaction, and the underlying processes, at a macroscopic and at a molecular level. The structure of this instructional design is described below:

1˙2.1. Presentation of the challenge and questioning. As all REVIR sessions, this one also starts by posing a question or problem to be solved by the students. It is contextualised around an inspection that has been carried out in a company that stores gases such as methane, hydrogen and argon and has detected a leak of a greenhouse gas (GHG). Then, the challenge presented to students consists of answering "How could they predict and determine which gas is a GHG?", and "How could they explain its behaviour?".

1˙2.2. Experimental design and data analysis. Once students have elicited their previous ideas about the greenhouse effect and GHGs, they are asked to design an experiment to analyse the macroscopic effects (temperature increase) of IR radiation-matter interaction on the gases' behaviour. The main purpose is to promote students' discussion on the variables affecting the experimental results and on how to control them. Once they have discussed the experimental setup, a whole class discussion ends up in an agreement to carry out an experiment consisting of preparing two systems simulating two atmospheres with different degree of CO_2 concentration: System 1 containing just water (apart from air); System 2 containing hydrochloric acid (apart from air) and adding

Fig. 1. – Experimental setup.

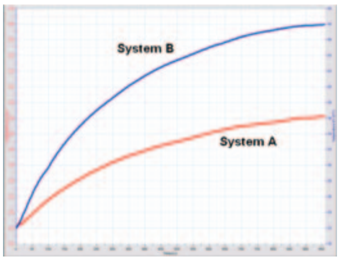

Fig. 2. – Graphical representation of the experimental result (temperature *vs.* time).

sodium bicarbonate. In System 2, a chemical reaction is produced and, as a result, CO_2 is created, which increases the concentration of this gas in this system (fig. 1). Each system is exposed to IR radiation keeping the same distance from the IR lamp.

Before carrying out the experiment, students make predictions about the evolution of the temperature in each system. Later, they use data-logging systems (temperature sensor) to collect data in a graphical form (fig. 2) during the experiment and to analyse the results. Finally, students are asked to draw conclusions about the macroscopic effect provoked by a higher concentration of CO_2 as a GHG(1).

In a later version of the instructional material, an additional exploratory question was posed and discussed with the whole group at the end of this section, asking students to explain how they think GHGs' temperature increase when interacting with IR radiation.

1·2.3. Visualisation at a molecular level. Students interact with a simulation(2) in order to explore the effects of different types of radiation (microwave, infrared, visible, ultraviolet) on molecules present in the atmosphere (carbon monoxide, nitrogen, oxygen, carbon dioxide, water, nitrogen dioxide, ozone). From this simulation, students have to infer the common behaviour of the molecules that interact with IR radiation (molecular vibration as a different effect from molecular rotation, electronic excitation or molecular bond breaking). Then, students are asked to relate the macroscopic behaviour (temperature increase) empirically observed in the previous section to the molecular behaviour (molecular vibration). In a later version of the instructional material, additional exploratory

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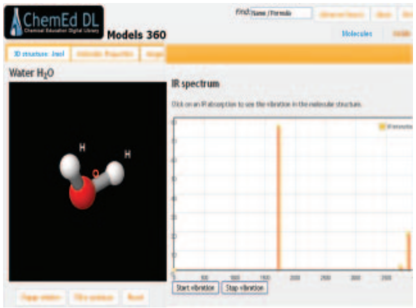
(1) The discussion of students' experimental results does not take into account the role played by water vapour in the increase of temperature as a GHG since, at this point, most students do not recognise this gas as a GHG yet. This point is discussed later during the activity sequence.

(2) `https://phet.colorado.edu/en/simulation/molecules-and-light`.



Click on an IR absorption to see the vibration in the molecule structure.

Fig. 3. – Theoretical IR spectrum of water molecules.

questions were posed and discussed with the whole group, asking students to invent an explanation of why molecules vibrate when IR radiation is emitted.

1·2.4. Discussion of a scientific interpretation. At this point, a scientific interpretation for this macroscopic and molecular behaviour is briefly discussed within the whole group of students. IR radiation is characterised by certain wavelengths and frequencies and also by a certain amount of energy that can be transferred. Different modes of molecular vibration are then associated to the internal energy of the GHGs, which is increased as a result of the absorption of part of the energy emitted by an IR lamp.

1·2.5. Application of the scientific interpretation in IR spectroscopy. Students are introduced to an IR spectrophotometer by means of a video and explore theoretical IR absorption spectra, using a molecule viewer(³). Substances are considered transparent to a certain type of radiation if part of the incoming energy is transmitted through it without producing effects. Students are expected to identify which gases can be considered GHGs depending on whether they present an absorption peak/band for certain IR frequencies in their IR spectra (fig. 3).

1·2.6. Solution of the initial challenge and application of knowledge to new questions. At the end of the session, students are asked again how to predict and determine which gas is a GHG. After discussing their answers with the whole group, students are asked to individually read an article(⁴) from a science magazine on a laser emitting IR radiation that is applied in acne treatments. This "IR laser" article explains that "the laser emits IR radiation with a specific frequency that fat can absorb more efficiently than water, and thus fat is heated and can be melted and destructed". From the reading of the "IR laser" article, students were asked to relate what is explained in this article to what they have learnt during this session.

2. – Theoretical framework

Regarding radiation-matter interaction, various authors have analysed students' understanding of greenhouse effect and global warming (Besson *et al.* 2010, Ekborg and Areskoug 2006, Koulaidis and Christidou 1999, Rye *et al.* 1997, Shepardson *et al.* 2011).

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(3) `http://www.chemeddl.org/resources/models360/models.php`.

(4) `http://www.muyinteresante.es/salud/articulo/desarrollan-un-laser-para-acabar-con-el-acne`.

According to these authors, common students' mental models or conceptions of EM radiation-matter interaction explain *enhanced* greenhouse effect in terms of:

- Atmosphere gases "trapping" all incoming solar radiation, but not Earth's radiation.
- Solar radiation heating but not getting out from the Earth because solar radiation weakens.
- The ozone layer depletion or the "ozone hole", provoking an increase of incoming UV rays, which warm up the Earth's surface.
- The energy released from cars' engines, instead of the CO_2 released.
- Specific gases released from human activities (*e.g.*, CO_2, CH_4, CFCs but not H_2O vapour).

Not so many research studies have focused on teaching and learning phenomena involving EM radiation-solid matter interactions (Redfors and Ryder 2001, Viennot and Décamp 2014). According to these authors, students tend to explain the effects of EM radiation-matter interaction on metals at different levels:

- Macroscopic level: In terms of processes taking place (*e.g.*, reflection, absorption).
- Mesoscopic level: In terms of bodies' surface properties (*e.g.*, "emissivity" or "reflectivity" of a body).
- Microscopic level: In terms of unbound electrons (free to move), excitation of atoms or molecules when colliding with photons, or atoms not providing photons room to pass.

For this research study, apart from considering previous research findings on students' conceptions of related phenomena, we have also considered literature reporting critical features of learning that affect people's abilities to transfer what they have learned (Bransford *et al.* 2004). In this sense, we have taken into account some of the following critical features of the instructional design in order to justify the types of changes made to consecutive versions of the designed instructional material to facilitate students' knowledge transfer from one context (GHGs) to another (IR laser):

- Amount and kind of initial learning: Focus on exploration or elicitation of students' previous conceptions.
- Students' motivation towards the topic or tasks.
- Time on task.
- Frequent feedback to support students' conceptual development, discussing students' interpretations during group discussions and asking explicit questions.
- Variety of contexts used.
- Metacognitive approach.

3. – Research questions

From the previous description of the activity sequence and the theoretical framework already discussed, we focused on students' development and use of explanatory models of the physical processes involved in specific socioscientific issues such as global warming and techno-scientific developments. With the purpose to understand the effectiveness of this designed instructional material, we conducted the research study presented here, which is intended to answer the following research questions:

RQ1. How do students conceptualise the processes (or mechanisms) that take place in IR radiation-matter interaction, and its effects at a macroscopic level and at a molecular level?

RQ2. How do these students' conceptualizations evolve in consecutive versions of the instructional design and interventions?

4. – Data collection and data analysis

Qualitative data were collected at the end of several REVIR sessions on the topic of IR radiation-matter interaction, via students' written responses to individual application open questions after reading the "IR laser" article described in section 6 of the activity sequence. Students' written productions in this task were conceived as the expression of their conceptions, which allow inferring qualities of their understanding.

We can distinguish three different stages of data collection:

- Academic year 2012-13 (S1): $n = 67$ students from 3 different schools. These students participated in the implementation of the first version of the instructional material. From the reading of the "IR laser" article, students were asked to *relate what is explained in this article to what they have learnt during this session.*

- First term of academic year 2013-14 (S2): $n = 49$ students from 2 different schools. These students participated in the implementation of the first version of the instructional material but from the reading of the "IR laser" article, they had to answer a more oriented application question: *How would you explain what happens to fat when it absorbs IR radiation emitted by the laser?*

- Second term of academic year 2013-14 (S3): $n = 119$ students from 5 different schools. These students participated in the implementation of the second version of the instructional material, which included further group discussion around specific exploratory and synthesis questions, and answered the second version of the application question from the reading of the "IR laser" article.

The collected data were analysed in an inductive manner to identify concepts and patterns on how students conceptualize IR radiation-matter interaction in students' responses. Inductive analysis as a qualitative methodology involves immersion into the details of the data in order to identify important categories, as opposed to imposing pre-existing expectations on the data. However, taking into account previous dimensions identified in the abovementioned literature, we classified emerging categories around three dimensions:

- Description of the effects of IR radiation-matter interaction at a macroscopic level (DMA)
- Description of the effects of IR radiation-matter interaction at a microscopic level (DMI)
- Explanation of the processes or mechanisms involved in IR radiation-matter interaction (EXP).

5. – Results

From the analysis of the collected data in each stage (*i.e.* students' answers to the individual application question posed at the end of each REVIR session from the reading of the "IR laser" article), we could define certain categories of students' responses of how they conceptualise IR radiation-matter interaction. Table I shows the relevant categories that emerged from the data analysis for each pre-established dimension as we constructed meaning from students' responses. Table I also shows examples of students' quotes to illustrate each category and the number of students' responses in each category.

Figure 4 summarises the percentage of students (from each stage of data collection) in each dimension whereas fig. 5 represents the percentage of students (from each stage of data collection) in each category.

Considering the results from S1, we evidenced that students tended to relate what they read in the "IR laser" article to what they had learnt during the session mainly highlighting the information from the article which had been explicitly discussed in class (*e.g.* temperature increase, selective absorption). Thus, most of students (55%) described the effects of IR radiation-matter interaction at a macroscopic level (DMA), mainly in terms of temperature increase and/or fat melting (DMA1), whereas very few students (7%) were able to describe the effects at a microscopic level (DMI). Similarly, although a high number of students (76%) were able to highlight some mechanism underlying IR radiation-matter interaction (EXP), most of them just mentioned the selective absorption of radiation as the main process involved (EXP2). Therefore, most students just repeated the information provided in the "IR laser" article, without establishing connections with concepts (*e.g.* changes to the modes of molecular vibration associated to the internal energy of the substances, absorption of part of the energy emitted by an IR laser) analysed throughout the REVIR session.

As these results were considered quite poor because of the little connection between the application task and the content tackled and discussed during the session, new data were collected in S2 from the new application questions posed after reading the "IR laser" article. The new version of the application questions was more explicit or oriented, trying to promote that students further described effects and explained underlying mechanisms or physical processes involved in IR radiation-matter interaction. Thus, this change to the application question was intended to facilitate students' knowledge transfer from the context used during the instruction (GHGs) to the one used in the application (IR laser for acne treatment). The analysis of these data (S2) provided evidence that a higher number of students (76%) were able to describe the effects of IR radiation-matter interaction at a macroscopic level (DMA), but also a higher number of students (45%) were able to describe the effects at a microscopic level (DMI), mainly in terms of molecular vibration (DMI1). Moreover, although a lower number of students (59%) were able to highlight absorption as an underlying mechanism involved in IR radiation-matter inter-

Table I. – *Emerging categories, students' quotes, and number of students' responses.*

Dimension	Categories	Students' quotes	S1	S2	S3
DMA (Description in terms of…)	… physical changes already mentioned in the “IR laser” article (*e.g.* temperature increase, fat melting) – DMA1	*“The contact between IR radiation and the skin heats the fat up and it melts”*	32/67	41/49	93/119
	… other changes not mentioned in the “IR laser” article (*e.g.* fat burning, composition change) – DMA2	*“Fat decomposes in simpler organic molecules”*	6/67	7/49	7/119
	Students do not describe effects at a macroscopic level	–	30/67	12/49	19/119
DMI (Description in terms of…)	… vibration of atoms/molecules – DMI1	*“Fat molecules start vibrating”*	4/67	13/49	44/119
	… weakening of molecular bonds – DMI2	*“If the molecules vibration is very high, molecules separate, their bonds break”*	1/67	3/49	37/119
	… changes to the modes of vibration of atoms/molecules – DMI3	“*Fat bonds can strain or bend*”	0/67	6/49	9/119
	Students do not describe effects at a microscopic level	–	62/67	27/49	43/119
EXP (Explanation in terms of…)	… absorption of radiation, already mentioned in the “IR laser” article – EXP1	*“There are molecules that can absorb IR radiation”*	5/67	4/49	0/119
	… absorption of certain radiation (λ/f), already mentioned in the “IR laser” article – EXP2	“*Fat produced by sebaceous glands can absorb the wavelength of the laser and so it gets burnt*”	42/67	21/49	42/119
	… absorption as a mechanism consisting of hindering the passage of radiation – EXP3	“*Fat absorbs laser's light, not letting it passes to muscular tissues*”	13/67	1/49	13/119
	… absorption as a mechanism consisting of a process of energy transfer – EXP4	*“The kinetic energy of particles increases and so does fat's temperature”*	2/67	6/49	28/119
	… absorption as a mechanism consisting of radiation detecting fat – EXP5	“*IR radiation enters into the skin and locates the fat*”	1/67	1/49	2/119
	Students do not explain any underlying mechanism	–	16/67	20/49	48/119

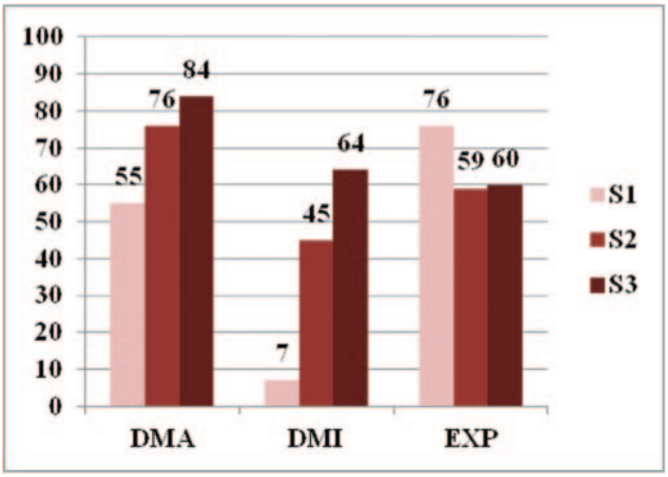

Fig. 4. – Percentage of students' responses (from each stage of data collection) in each dimension.

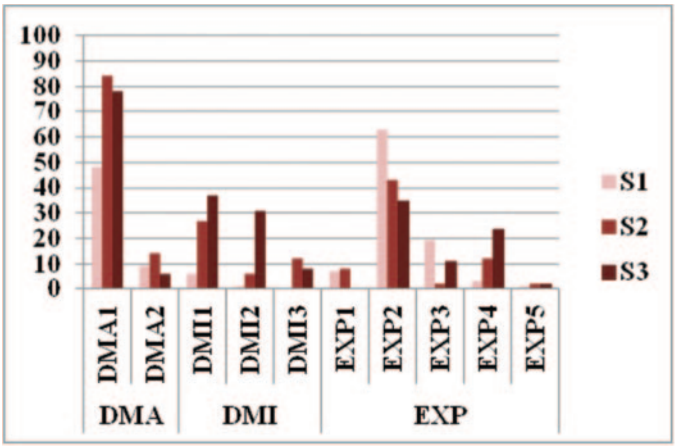

Fig. 5. – Percentage of students' responses (from each stage of data collection) in each category.

action, a slightly higher number of students (12%) were able to explain absorption in terms of energy (EXP4) instead of just in terms of radiation (EXP1/EXP2).

In spite of a remarkable decrease from S1 to S2 in the number of students' answers just repeating pieces of information from the "IR laser" article, we also identified certain students' difficulties in describing the effect of IR radiation-matter interaction at a microscopic level (DMI) and in explaining underlying mechanisms (EXP). For instance, many students from S2 expressed that molecular vibration is the effect of the absorption of IR radiation, as if molecules did not vibrate without any interaction with IR radiation. Another example is that very few students were able to explain absorption in terms of energy (EXP4) although section 4 from the activity sequence was explicitly devoted to discuss this scientific interpretation. Taking into account the previous results, further exploratory and synthesis questions were included and discussed with the whole group in a later version of the activity sequence, as described above. The results of the analysis of data from S3 provided evidence that not only a higher number of students (84%) were able to describe the effects of IR radiation-matter interaction at a macroscopic level (DMA), but also a higher number of students (64%) were able to describe them at a microscopic level (DMI). Moreover, a higher number of students (24%) were able to explain absorption in terms of energy (EXP4) instead of in terms of radiation (EXP1/EXP2).

6. – Conclusions

From this research study, we have been able to analyse students' conceptualizations of the processes or mechanisms that take place in IR radiation-matter interaction, and its effects at a macroscopic level and at a molecular level (RQ1). The analysis of students' answers from S1 provided evidence that many students were able to conceptualize the effects resulting from IR radiation-matter interaction in macroscopic terms (temperature increase), but not so many students were able to describe these effects in microscopic terms (molecular vibration). We might interpret this result in terms of students' difficulties to relate the effects at a macro and micro level, but it might be also interpreted in terms of the type of application used (too general) or in terms of aspects of the instructional design and intervention. We also evidenced that most students identify selective absorption of radiation as the main mechanism involved in IR radiation-matter interaction, which is relevant. However, very few students were able to transfer their knowledge from one context to the other about energy transfer in explaining the mechanisms underlying IR radiation-matter interaction.

With regards to RQ2, we have evidenced that the introduction of more oriented application questions and the discussion with the whole group on exploratory and synthesis questions during the instruction resulted in a greater number of students' descriptions in macroscopic and microscopic terms, a lower number of information explicitly repeated from the "IR laser" article, and a slightly higher number of explanations in terms of energy.

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