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Secondary Students' Analogical Reflections on Unfamiliar Scientific Concepts

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Abstract: In this paper, we describe a method of reflection, analogical reflection, and present a supportive software tool, called ART (Analogical Reflection Tool). We focus on the contribution of analogical reflection to students' comprehension of unfamiliar scientific concepts. There are two basic categories of reflection: self-reflection and comparative reflection. In self-reflection, the learner reflects on his or her own actions. In comparative reflection, the learner reflects on others' actions. We propose an alternative reflection type as a subcategory of comparative reflection: analogical reflection. In analogical reflection, students reflect on analogies, collating their actions with the analog's functions. The hypothesis of our research is the following: If the learners study an analogical model, they will improve their performance, comprehending the unfamiliar scientific concept "electric capacitance" and identifying their alternative conceptions. According to the results, analogical reflection on unfamiliar concepts through ART appeared to be effective only after the students completed the learning activities. ART guides the students to make use of their existing knowledge, comprehend the studied domain, revise their alternative conceptions, and validate their correct perceptions.

Keywords: Analogies, Modeling, Reflection

Introduction

Students often accept their teacher's instructions passively, memorize lecture notes and books, and solve problems by following routines that the teacher had highlighted during lectures. If the teacher presents information that is contrary to the students' perceptions, they rarely reflect on it (Halloun 2006). Reflection may improve students' exploratory ability and metacognitive skills. Reflection after a collaborative, exploratory activity may lead students to think about how they could improve their actions. Thus, students who are engaged with reflection and scientific practice better understand the goals and purposes of research (Schön 1983; White, Shimoda, and Frederiksen 1999). Reflection becomes easier and more effective when students take an active role, such as that of the researcher (Elbers 2003).

Reflection is a cognitive activity in which individuals explore their experiences to reach new perceptions (Boud, Keogh, and Walker 1985). In reflection, the person not only gathers information on the course, but also goes a step beyond awareness, by evaluating the available information and judging whether it is consistent or inconsistent with his or her views. Providing information is not enough to change the perceptions of students (Prins, Sluijsmans, and Kirschner 2006). The student must also manage the information to accept it as correct or to dispute it as incorrect (Kritikos and Dimitracopoulou 2014; Phielix et al. 2011). If the information contradicts one's perceptions, one is driven to self-regulation, by revising the existing perceptions.

Reflection may take place during an activity (reflection-in-action) or at the end of an activity (reflection-on-action) (Manlove 2007; van Joolingen et al. 2005). Reflection-on-action corresponds to the evaluation at the end of the activity, while reflection-in-action is a kind of monitoring of the activity's progress. Reflection-on-action emerges from the requirement to summarize and evaluate the entire activity. On the other hand, through reflection-in-action students monitor specific stages of the activity and reassess their progress.

There are several ways to promote reflection in technological learning environments. Common examples include: (1) dialogues between the learning system and the learner (Tsaganou, Grigoriadou, and Cavoura 2004; Tsovaltzi and Fiedler 2003); (2) software agents with specific roles (White, Shimoda, and Frederiksen 1999); (3) concept maps (Cimolino, Kay, and Miller 2003; Toth, Suthers, and Lesgold 2002); (4) conflict awareness simulations, which accent strange behaviors (Hirashima and Horiguchi 2003); and (5) interaction analysis tools (Phielix, Prins, and Kirschner 2009). White, Shimoda, and Frederiksen (1999) used the SCI-WISE agent-based software, in which each agent has a role to accomplish specific targets. Such agents are the Planner, Collaborator, Assessor, Inventor, and Analyzer. The inquiry activities follow the cycle: Question – Hypothesize – Investigate – Analyze – Model – Evaluate. At the beginning, students receive a question about a phenomenon, and they make a hypothesis for investigation. Then, students analyze the results and start modeling. Finally, they evaluate the results, completing the cycle. At this last stage, students reflect on the entire activity, searching for their model's limitations.

Analogical Reasoning

Analogical reasoning is a mental process by which learners adapt their knowledge from a familiar cognitive domain to an unfamiliar domain. Through analogical reasoning, students exploit their own existing knowledge in the familiar domain to understand the studied domain. The two domains are similar in their structure and/or functionality, and students must be capable of analyzing and comparing them. The analogical system is the "source," and the system under study is the "target." One target may be related to sources from different domains. For example, a computer network (target) could be represented by different analogs (sources), such as road network, rail network, or post office.

If a characteristic/function of the source shares similarities with the target, then the analogy is positive, but if the characteristic/function is opposite from the target, then the analogy is negative. If the characteristic/function of the source seems similar to one of the targets, but it is not actually relative, then the analogy is neutral (Harrison 2001).

Figure 1 shows an analogical model (analog) for electric capacitance. The analog consists of a tap that is filling a glass with water. The glass capacity is independent of the water and the tap, and the electric capacitance is independent of the electric charge and the voltage source.

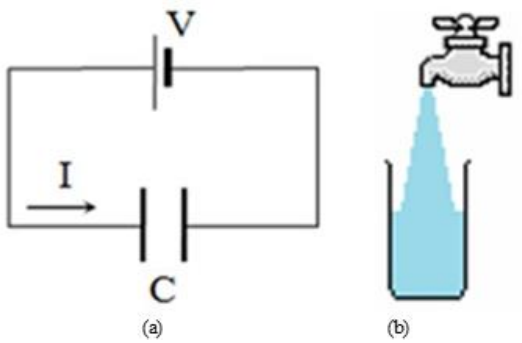

Figure 1: (a) capacitor charging model; (b) glass filling analog

Between the capacitor charging model and its analog (glass filling), there are positive, negative, and neutral analogies. Table 1 provides some examples.

Table 1: Analogies between the "capacitor charging model" and the "glass filling analog"

Analog	*Capacitor charging model*	*Glass filling analog*
Positive	1. The electric capacitance depends on the geometrical dimensions of the capacitor. 2. The electric capacitance does not depend on the electric charge. 3. The electric capacitance does not depend on the voltage source.	1. The capacity of the glass depends on the geometrical dimensions of the glass. 2. The capacity of the glass does not depend on the water. 3. The capacity of the glass does not depend on the tap.
Negative	1. The electric capacitance refers to the maximum electric charge, according to 1 Volt of voltage. 2. When a dielectric material is added between the capacitor's conductors, the capacitance increases.	1. The capacity of the glass refers to the maximum water quantity, independently of the tap's supply. 2. When a material is added inside the glass, the capacity decreases.
Neutral	1. The capacitor may be cylindrical.	1. The glass may be cylindrical.

The electric capacitance C may be found from the equation $C=Q/V$, where V is the potential difference (voltage) between the capacitor's conductors and Q is the electric charge of the capacitor. A common alternative conception of students derives from this relation. Students consider that the capacitance is proportional to the electric charge and inversely proportional to the voltage. They do not distinguish the independent from the dependent and the constant values. The capacitance is independent of both the electric charge and the voltage. Greater voltage causes larger electric charge, while their ratio is constant and equal to the capacitance.

An analog to the electric capacitance is the capacity of a glass. A typical glass has a capacity of 250 mL, regardless of the water quantity it contains or the tap that fills it. The capacity of the glass may change if its dimensions change. Respectively, the electric capacitance may change if its dimensions change (positive analogy). Based on the analogical model of the glass, it is clear that the electric capacitance depends on its geometrical dimensions, while it does not depend on the electric charge or the voltage.

However, while the source (glass) and the target (capacitor) are identical, there are critical differences between them. The electric capacitance refers to the maximum electric charge per 1 Volt of voltage, while the capacity of the glass refers to the maximum water quantity, independent of the tap's supply (negative analogy). For example, the electric charge of a 5 Farad capacitor is 5 Coulombs when the voltage is 1 Volt, 10 Coulombs when the voltage is 2 Volts, 15 Coulombs when the voltage is 3 Volts, etc. Instead, a 250 mL glass fills with 250 mL of water, regardless the tap's supply. Another negative analogy is that the electric capacitance increases when one adds a dielectric material between its conductors. The capacity of a glass decreases when one adds a material inside the glass. Negative analogies may generate alternative conceptions to students and, therefore, must be clarified.

Analogical Reflection

When learners reflect on their own actions, they may improve their metacognitive skills. If learners study an analogical model instead of the target domain, the revision may be substantial, because they may find their errors through their own existing knowledge from the familiar source domain of the analogical model. There are two basic categories of reflection: self-reflection and comparative reflection. In self-reflection, the learner reflects on his or her own actions, by monitoring his or her own reasoning (Schön 1983). In comparative reflection, the learner reflects on others' actions (Elbers 2003). Others could be classmates, the teacher, textbooks, or anything aside from the learner. In groupware learning environments, comparative reflection is known as collaborative reflection or co-reflection (Phielix et al. 2011). This kind of reflection combines self- and comparative reflection. We propose an alternative reflection type as a subcategory of comparative reflection: analogical reflection. In analogical reflection, students reflect on analogies, collating their actions with the analog's (analogical model) functions (Figure 2). During the collation, students correlate the source with the target.

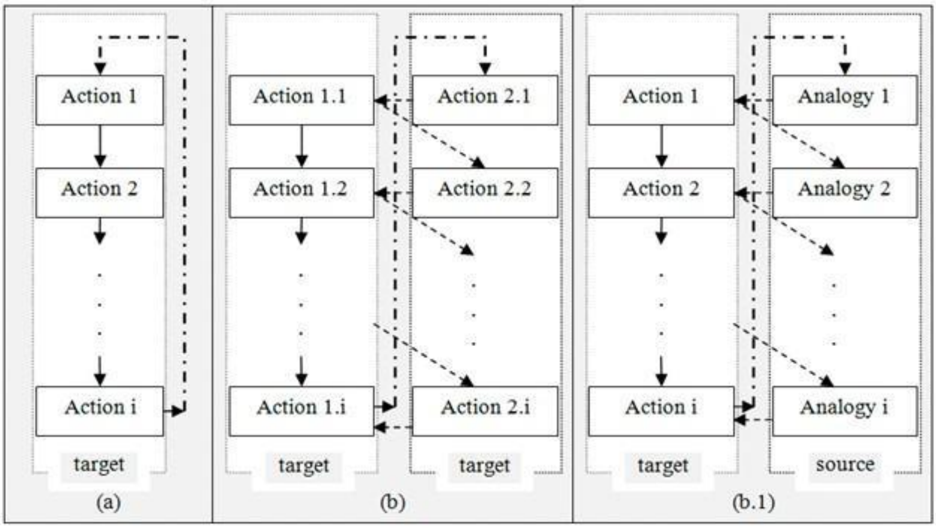

Figure 2: (a) reflection types: (a) self; (b) comparative; (b.1) analogical

The idea to introduce and examine analogical reflection derived from the combination of analogical reasoning with comparative reflection:

<u>Analogical</u> Reasoning + Comparative <u>Reflection</u> = Analogical Reflection

At this point, we have to make clear that analogical reflection is more than a mapping between the source and the target. Mapping is the part of analogical reasoning that aims to make the context understandable. When students study an analog in order judge, review, reallocate, and validate their cognitive backgrounds, they reflect on their actions through the analog. This is what we call analogical reflection.

Method

ART (Analogical Reflection Tool)

ART (Analogical Reflection Tool) is a scaffolding software tool that we have designed to assist students with reasoning and reflecting analogically. It consists of five concrete stages: Model's Description; Analogies' Record; Analog's Description; Analogies' Validation; and Analogies' Report. The main idea is that the user reflects on the source domain (analog) in order to understand the target domain (Figure 3).

Figure 3: ART's splash screen

To begin using ART, the student enters his or her personal data (name, etc.) and then gains access to five concrete stages. At the first stage, Model's Description, students describe the model that they had created previously in modeling software, such as Modellus (White, Shimoda, and Frederiksen 1999; Teodoro and Neves 2011). The description includes the model's entities, parameters, and functionality. The second stage is Analogies' Record, where students correlate their actions during the model's creation with analogies (positive, negative, neutral) from an analogical model they received. We changed the terms positive and negative analogies to real and misleading, respectively, to be more suitable to the students' perceptions. At the following stage, Analog's Description, students study a description of the analogical model, including the analog's entities, parameters, and functionality. At the fourth stage Analogies' Validation (Figure 4), students validate, change, or even delete any analogy that they had recorded at the Analogies' Record stage, or they add a new one (Cimolino, Kay, and Miller 2003). At the last stage, Analogies' Report, the software provides a report that presents students with a summary of their work, so that they can reflect on it. This is the stage in which a kind of "student model" appears to the students, similar to Open Learner Model systems (Tsaganou, Grigoriadou, and Cavoura 2004; Tsovaltzi and Fiedler 2003).

The report consists of five tabs: Real Analogies, Misleading Analogies, Neutral Analogies, Deleted Analogies, and Total Actions. In particular, the report includes all the real (positive), misleading (negative), and neutral analogies that students recorded/validated, changed, or deleted. The Total Actions tab presents the number of the initial recorded analogies (Analogies' Record stage), the final validated analogies, and those that had been changed, added, or deleted separately for each type of analogy. Finally, the user saves his or her data from ART in a file (*.art) for future use.

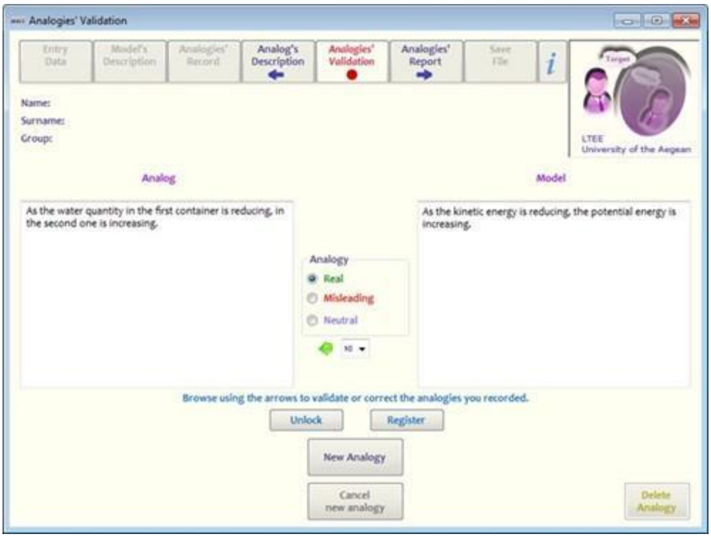

Figure 4: ART's screen in Analogies' Validation stage

ART guides students step-by-step to reason and reflect analogically. At the first stage, students have to describe the model that they had created previously in a modeling software, such as Modellus (Teodoro and Neves 2011). The description includes magnitudes (such as kinetic, potential, and mechanical energy, mass, height, and inclination) and the relations between them. At the second stage, students correlate their actions with analogies (real, misleading, neutral) from the analogical model. For example, they correlate the relation between kinetic and potential energy with the water transfusion from one container to another. Consequently, students have to justify why they equalized the kinetic energy reduction with the potential energy increment. At the third stage, students study a description of the analogical model (including entities, parameters, and functionality), while at the fourth stage they have to validate, change, or delete each analogy that they had recorded previously, or add a new one. If a student made a mistake during the modeling activity and did not realize it at the Analogies' Record stage, then he or she may identify the mistake through the analog's description. Therefore, students review their modeling activity by reflecting on the analog. Students complete their analogical reflection at the fifth stage, as they watch their total actions in ART. They review what they had recorded before examing the analog's description and what they had changed afterwards. Deleted analogies indicate strong alternative conceptions (according to data from our research) before analogical reflection. For example, a student initially may correlate the mass of the body with the quantity of the water, which is wrong. If, after the analogical description, he or she deleted the analogy, the Deleted Analogies tab in the final report of ART will highlight this revised alternative conception (Kritikos and Dimitracopoulou 2014).

Research Question and Hypothesis

The main question of our research is, "What is the impact of analogical reflection on students' comprehension of unfamiliar scientific concepts (electric capacitance)?" The hypothesis of our research is that there is a relationship between the learners' reflections on an analogical model and their performance, concerning their comprehension of the unfamiliar scientific concept electric capacitance.

Participants

The participants were 12 secondary high school students, aged 15 years. The students worked collaboratively in three groups. Each group consisted of four students with various performance abilities in physics. Two students in each group were at a high performance level (20/20 term grade), one was medium performance (15/20 term grade), and one was low performance (10/20 term grade). Each group consisted of two pairs of students, with each pair consisting of one high performance and one medium or low performance student. Each pair worked on the same computer and collaborated synchronously with the other pair.

Learning Tasks and Environment

To begin, the students attended a 20-minute instructional presentation of the concept electric capacitance. The presentation was teacher-centered, without any interaction between the students and the teacher. The aim of the presentation was only to inform the students about electric capacitance, an unfamiliar concept. Then, the students studied a model of an electric circuit with a capacitor, which was charging from a voltage source. The teacher created the model in the technology-based modeling software Modellus (Teodoro and Neves 2011). After studying the model, the students answered a pre-test, regarding electric capacitance. Subsequently, the students studied a given analogical model, created in ART and consisting of a glass being filled with water from a tap. After studying the analogical model, the students worked step-by-step in ART. Finally, the students answered a post-test (same as the pre-test).

The study required the students to use four software programs. The modeling software Modellus allowed students to study the model and the analog. The collaboration tool TeamViewer allowed both pairs of students to work on a common modeling space, while also providing a chat space. Camtasia allowed students to capture video and collect data during the self-reflection phase of the activities. ART, as an analogical reflection tool, supported the students as they reflected on the analogical model.

Design and Data

At the beginning of the capacitor modeling activities, we gave students a pre-test consisting of 15 closed format questions, regarding their perceptions about electric capacitance. In order to measure the impact of the modeling activities on students' comprehension of electric capacitance, we gave the same questionnaire (pre-test) to students as a post-test after they completed the activities.

In order to study the main research question, we discriminated between analogical reflection in action and on action, regarding whether the reflection took place during the study of the analog or after the completion of the study. Thus, we used a 1x2 factorial design with the following factors: (a) ARi, analogical reflection in action, and (b) ARo, analogical reflection on action.

We collected the data for ARi from Camtasia's captured videos, in the Analogies' Validation stage. In order to measure the impact of ARo on students' comprehension of the unfamiliar scientific concept electric capacitance, we created a test, which we administered to the students before (pre-test) and after (post-test) the use of ART. The test consisted of 15 closed questions regarding electric capacitance.

The Analogies' Validation stage of ART guides the students to reflect in action. This stage follows the Analog's Description stage, which aims to enforce ARi, right after the analogical reasoning portion of the previous stage, Analogies' Record. On the other hand, the logfiles (*.art) extracted from ART in the Analogies' Report stage enforce ARo.

We measured the impact of ARo on the students' comprehension of electric capacitance by comparing the pre-test with the post-test and after the use of ART. We tested the statistical significance of the differences between the pre-test and the post-test through the use of a t-test on the following null hypothesis (Ho): "ARo does not contribute to the comprehension of the unfamiliar concept electric capacitance."

Finally, we analyzed the students' dialogues and arguments to detect whether they exploited their knowledge about the familiar domain of the analog to identify their alternative conceptions. In analyzing the dialogues and arguments we also investigated the potential risk of generating alternative conceptions by false analogies.

Results

ARi

Table 2 provides the number of positive, negative, and neutral analogies each group of students (A, B, C) recorded. Groups A and C recorded more positive than negative analogies, while group B recorded more negative than positive analogies. None of the groups recorded any neutral analogies.

Table 2: Number of analogies recorded in ART

Group	*Positive*	*Negative*	*Neutral*	*Total*
A	3	2	0	5
B	1	4	0	5
C	3	0	0	3
Total	7	6	0	13

Table 3 provides the number of added, deleted, or changed analogies at the Analogies Validation stage of ART. It is obvious that the Analog's Description stage, which students entered after the Analogies' Record stage, did not cause any significant effect. The students did not add or delete any analogies during the Analogies' Validation stage. The only change in one analogy regarded the syntax of its sentence. Therefore, there were no obvious signs that the Analog's Description contributed to the Analogies' Validation. Thus, ARi did not affect students' comprehension of the unfamiliar concept electric capacitance.

Table 3: Number of analogies added/deleted/changed in ART

Group	*Added*	*Deleted*	*Changed*	*Total*
A	0	0	1	1
B	0	0	0	0
C	0	0	0	0
Total	0	0	1	1

ARo

We measured the impact of ARo on students' comprehension of the unfamiliar scientific concept electric capacitance by comparing the pre-test with the post-test and after the use of ART. Table 4 provides descriptive statistical data on the pre-test and the post-test.

Table 4: Descriptive statistical data on the pre-test and the post-test (high score: 15)

	min	*max*	*M*	*SD*
Pre-test	6	13	8.67	2.10
Post-test	7	13	10.75	1.96

The mean of the students' grades on the pre-test was $M = 8.67$ ($SD = 2.10$), while on the post-test $M = 10.75$ ($SD = 1.96$). Thus, there was an improvement of 2.08 units, according to the high score of 15.

We used a t-test on the following null hypothesis (Ho) to test the statistical significance of the differences between the pre-test and the post-test: "ARo does not contribute to the comprehension of the unfamiliar concept electric capacitance."

The t-test results showed a significant difference ($t = -4.795$, $p = .001 < .01$) between the pre-test and the post-test. Therefore, ARo affects positively students' comprehension of the unfamiliar concept electric capacitance.

Students' Clarification of Alternative Conceptions

Analysis of the students' dialogues and arguments show that many students ($n = 8$, $f = 67\%$) identified their alternative conceptions by exploiting their knowledge of the familiar domain. Table 5 provides examples of the students' comments during a capacitor modeling activity.

Table 5: Identified alternative conceptions by analogies, according students' comments

Analogy	*Identified alternative conception*
S.4: "The capacity of the glass does not depend on whether the glass is filled, like the capacitance of the capacitor does not depend on whether it is charged."	The capacitance of the capacitor is proportional to the charge, according to the relation $C=Q/V$.
S.6: "The capacitance of the capacitor depends on the geometrical characteristics, like the glass does."	The capacitance of the capacitor depends on the charge and the potential difference, according to the relation $C=Q/V$.
S.10: "The voltage source charges the capacitor, like the tap fills the glass."	The capacitor and the battery exchange charge.

The Risk of Generating New Alternative Conceptions by False Analogies

The exploitation of familiar knowledge from the analog (source) may contribute to students' understanding of the unfamiliar model (target). However, the analog is not identical to the model. Therefore, a false correlation between them could generate new alternative conceptions. Such alternative conceptions are usually derived from the negative (or neutral) analogies, which are perceived as positive. Thus, we investigated the *.art logfiles of the students to identify the false analogies and their alternative conceptions. Table 6 presents all the false analogies and the corresponding alternative conceptions that the students concluded during a Mechanical Energy modeling activity. Of the 13 total analogies the students recorded, three were false (n = 3, f = 23%).

Table 6: Alternative conceptions by false analogies, according to students' comments

False Analogy	*Alternative conception*
"The flow of the water remains constant, like the volume of the capacitor remains constant."	The tap corresponds (analogically) to the voltage of the capacitor. They considered the magnitude V (at the relation $C=Q/V$) as the volume of the capacitor.
"The amount depends on water from the glass volume, like the capacitor depends on	The amount of water corresponds (analogically) to the capacitor.

the capacitance."	
"Even if we add slowly the water, the glass will overflow. If we increase the voltage slowly, the capacitor will be fully charged."	In order to fully charge the capacitor, the voltage must increase.

Conclusions and Discussion

To study the contribution of analogical reflection to students' comprehension of unfamiliar concepts, we examined whether students identify their alternative conceptions through analogical reflection, and in parallel we investigated the risk of generating new alternative conceptions by false analogies.

According to the results, students detected the positive analogies easily, the negative analogies less easily, and the neutral analogies rarely. Many students searched for the negative analogies, but most of them failed. This means that real and substantial similarities, or positive analogies, are those which play the most important roles in analogical reasoning, while negative analogies are difficult to detect, and neutral analogies are almost undetectable. This increases the risk of generating alternative conceptions by identifying the model with the analog, because all analogies will be considered positive. Therefore, further guidance is necessary for identifying mainly negative analogies, to reduce the risk of developing alternative conceptions in analogical reasoning due to similarities. Based on this outcome, we investigated the risk of generating alternative conceptions by false analogies.

The analog is not identical with the model that students study. Hence, a false correlation between them may create alternative conceptions. Such alternative conceptions are usually derived from the negative or neutral analogies, when students consider them as positive. From the students' *. art logfiles we detected the false analogies and the corresponding alternative conceptions which the students had recorded. The false analogies comprised three of the 13 total, or about 23%. Given that: (a) students have many alternative conceptions and significant difficulties regarding the study of electrical circuits (Kollöffel and de Jong 2013; Vreman-de Olde and de Jong 2004) and (b) there were only a few false analogies (n = 3, f = 23%) at the analogical reflection stage iART, we claim that analogical reflection, supported by ART, benefitted the students' comprehension of unfamiliar scientific concepts (electric capacitance). Thus, the risk of generating alternative conceptions by false analogies is minor.

Although we detected mostly positive analogies from the students during analogical reasoning, most of the students did not have alternative conceptions. The students clarified their alternative conceptions, based on knowledge of the analog. When we compared the clarification of alternative conceptions through their self-reflection on action and ARo, we found significant differences, indicating that analogical reflection caused better results. Therefore, the contribution of ARo in the clarification of alternative conceptions was greater than that of self-reflection on action.

We examined the contribution of ART in analogical reflection through two cases, ARi and ARo. The Analogies' Validation stage of ART guided the students in ARi. Analogies' Validation follows the Analog's Description stage, which aims to enhance ARi following analogical reasoning during the previous stage, Analogies' Detection. The ARi of the Analog's Description stage, which students received right after the Analogies' Detection stage, did not cause any change. Therefore, ARi through ART did not appear to improve students' comprehension of the unfamiliar concept electric capacitance.

The stage of reflection (especially ARi) requires students to have an elementary level of knowledge, either during (ARi) or after the end of the activities (ARo). An introductory instruction, such as the one in our research, would particularly benefit high performance students. Students with lower performance abilities in physics should pass the threshold of basic knowledge, including fundamental concepts, in order to move up to the level of metacognition through reflection. Thus, ART appears to be more beneficial to high performance students and even more at ARo.

In conclusion, analogical reflection on difficult and unfamiliar concepts through ART appears to be effective only after students complete the activities. When students study a model, they focus mostly on the multiple representations produced by the modeling software, but not on the familiar analog. On the other hand, when they reason analogically within a specific environment, such as ART, with the proper guidance they can exploit their existing knowledge of the familiar domain of the analog. Essentially, ART guides the students to use their existing knowledge to better comprehend the studied model, revise their alternative conceptions, and validate their correct perceptions through ARo (their evaluation at the end of the activity).

The findings from the current study could be the basis for further research, concerning other concepts of physics or science, or even other disciplines (history, literature, etc.). ART could be utilized in any course that exploits analogical reasoning, aiming at the transition from the cognitive to the metacognitive through reflection.

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