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The formation of visual-verbal paired associates for resistor-capacitor series circuits

Sarah Pulé†‡

University of Malta, Msida, Malta†
University of Loughborough, Leicestershire, England, United Kingdom‡

ABSTRACT: Dual coding theory suggests that mental representations are associated with distinct verbal and nonverbal symbolic modes. Undergraduate engineering, and design and technology students tend to develop and cultivate strong, rigid associations between the words *charging* and *discharging*, and particular exponential graph shapes when studying the topic of resistor-capacitor series circuits. The scope of this study was to investigate if students possessed inflexible visual-verbal links, which hindered the application of conceptual knowledge to similar, but unfamiliar circuit configurations. The use of structured interviews was one of the options for collecting the data to support the conjecture mentioned. Qualitative analysis revealed that through traditional teaching and self-learning methods, students foster visual-verbal relationships, which in time become strong paired associates and hinder the application of the conceptual knowledge they posses to topologically similar, but unknown circuits. This outcome is of particular significance to teachers of electrical engineering, physics, and design and technology since all these professions cover the topic of resistor-capacitor circuits in various forms and levels.

Keywords: Dual coding theory, visual-verbal, paired associates, resistor-capacitor circuits

INTRODUCTION

This study reports on one aspect of a larger research project, which investigated participants' insight regarding resistor-capacitor series circuits. The work here focuses on a qualitative investigation of participants' tendency to develop associations between verbal and visual information pertinent to the topic in question. The article starts by giving a brief overview of the typical characteristics of the quality of students' learning. It, then, presents Clark and Paivio's dual coding theory as a possible explanation for the observed phenomena, apart from difficulties such as graph interpretation, which the participants might experience [1]. The findings suggest that when learning about resistor-capacitor circuits, students cultivate strong, rigid associations between the words *charging* and *discharging*, and particular exponential graph shapes as in Figure 2 and Figure 3 presented later in the article. These connections seem to inhibit students from applying the conceptual knowledge they posses on the topic to topologically similar, but unfamiliar circuit cases. The source of this problem may point to teaching methods or course materials, which repeatedly emphasise the same illustrative examples, rather than promoting a more general method of teaching the concept concerned.

The Characteristics of Students' Learning

Students seem to bring with them the motto: *Why think when you can memorise?* [2]. Students tend to put their faith in memorisation and resist thinking. Entry requirements into tertiary educational institutions for engineering and technical teaching undergraduate courses, such as those at the University of Malta, require students to have attained some basic learning outcomes. These would entail the ability to describe in detail the relationships between a scientific or technological concept and the formalism such as diagrams, graphs, equations, etc, used to represent it. As learning outcomes, it would also be expected that students are able to apply concepts and the respective representations to the analysis and interpretation of scientific and technical phenomena, and also make explicit the correspondences between a concept and an event in the real world [3].

Unfortunately, research indicates that while most students can recall simple facts or do simple computations, they exhibit serious deficiencies when dealing with higher levels of scientific and technological thinking [4]. It seems that experience has taught these students that they are likely to succeed in their examinations if they remember enough details, equations and worked examples [2]. Faced with simple, but unanticipated situations, students are not able to apply the necessary reasoning. Regrettably, the ease with which they use technical jargon or have the ability to follow prescribed procedures for solving standard problems is not an indication of conceptual understanding [3]. Contributing to this problem may be the fact that students' education may be driven by assessment practices and philosophies that emphasise mechanistic knowledge gain rather than knowledge application. Even if these practices successfully impart facts and rote skills to most students, they fail to convey higher order thinking [4][5]. Research in mechanics and electricity has provided ample evidence to indicate that traditional problem solving methods limit students' authentic learning of the concepts concerned [6-8].

Dual Coding Theory

Dual coding theory postulates that mental representations are associated with distinct verbal and nonverbal symbolic modes and retain the properties of the concrete sensorimotor events on which they are based [1]. While verbal modes refer to linguistic symbols, which are, to an extent arbitrary, nonverbal representations include images, sounds, actions and skeletal or visceral sensations related to emotion, which are analogous or perceptually similar to the events they denote. Dual coding theory explains psychological phenomena by the combined action of verbal and nonverbal systems. These systems are composed of mental structures and processes. Mental structures are networks of associations between verbal and nonverbal representations, while processes concern the development and activation of the said structures. Connections within the structures can be of two types: referential, which join corresponding verbal and nonverbal codes; for example, imaging to words and picture naming; and associative, which join representations within the verbal and nonverbal systems; for example, word to word or picture to picture. Research evidences the enhancement of memory if verbal information is presented with visual information and vice versa. It was also found that students are more likely to generate mental images if instructed to do so, rather than if left to their own devices. Besides, instructions and related context were found to influence not only the relative activation of verbal and nonverbal systems, but also the patterns of activation within these same systems. Therefore, teaching methods, intentionally or unintentionally, can prime classes of responses for subsequent items. The role of past experience is recognised as being of central importance to the development of mental representations within dual coding theory. Experience is accumulated through formal teaching and also through self-learning. The act of reading alone seems to elicit substantial amounts of uninstructed imagery. According to dual coding theory, meaning and cognitive structure are the outcomes of associations in between the verbal and nonverbal systems. Jointly, these systems determine learning and memory performance, and influence storage and retrieval of information.

The Difficulty with Graphical Representations

The difficulty with understanding complex concepts in scientific knowledge may be compounded with difficulty in the interpretation of certain representations; for example, graphs. One study showed that undergraduate physics students seem to lack the ability to use graphs to extract or convey information [9]. Most students, apparently, had the necessary skills to draw graphs through an algorithmic procedure and, therefore, the difficulties experienced did not surface in the course of traditional instruction. The list of graphing errors identified by McDermott's study reflects that many are a direct consequence of students' inability to make connections between a graphical representation and the subject matter it represents. Indeed, the practical application of graphical skills in any field does not involve remembering, but interpretation.

A deeper knowledge than memory is required when a problem requires a type of analysis for which the student does not have a pattern. In such cases, simply remembering procedures is not sufficient. For the kinematics problems used in McDermott's study, it was clear that few students were able to obtain a qualitative overview of the object's motion by reading the graph because they did not interpret and form a mental picture or visualise the motion depicted in the graph. Students studying scientific or technical subjects should be able to represent real systems graphically and to visualise systems from their graphical representations. The ability to translate back and forth in between real-life, practical or laboratory situations into graphical representations is considered an important component of understanding subject matter. This means that realistic assessment of student ability to extract information from a graph must involve elements of interpretation and not memorisation.

Paired Associate Learning

Paired associate learning is the combination and learning of syllables, digits, words or pictures in pairs so that one member of the pair evokes recall of the other [10][11]. This occurs when the stimulus member of the pair serves as a *conceptual peg* to which its associate is hooked while the learning takes place with both members being presented together. Consequently, the response member can be retrieved on recall even when the stimulus member is presented alone. As discussed from the section below, mental code switching between verbal and nonverbal information is an important referential activity. Dual coding theory postulates that related verbal and nonverbal representations are directly connected and are most probably determined and maintained by the number, type and recentness of experiences with referring to objects by name. The ease of translation between verbal and nonverbal representations is expected to be positively correlated, so the strength of connections in one direction provides opportunities for strengthening the operations in the opposite direction. Presumably, the arousal of the said operations can be influenced by instructions given to subjects.

RESEARCH QUESTIONS

The research questions addressed in this study are the following:

1. Do participants develop visual-verbal paired associations between graphs and technical jargon for the topic or resistor-capacitor series circuits? Is this a help or a hindrance?
2. Do participants transfer the knowledge acquired about familiar resistor-capacitor circuits successfully to unfamiliar resistor-capacitor circuit configurations?

Table 1 lists in detail the possible referential and associative links, which may be developed by students on the topic of resistor-capacitor series circuits throughout their learning experience. It is conjectured that referential links may be present from the verbal domain of the words, *charging* or *discharging*, to the nonverbal domain of the circuit diagram, the graphical representation and hand gestures. Associative connections may also be present in between the latter three nonverbal representations. This article investigates only the links that might be present between the words, the circuit diagrams and the graphs.

Table 1: A dual coding theory representation of the referential and associative connections for the topic of resistor-capacitor series circuits prior to a novel teaching intervention.

Verbal	Nonverbal		
●— Referential connections	—●——————●——————●		
	Associative connections ●——————●——————●		
	Visual Imagery		Kinaesthetic Imagery
The word *charging*	Circuit diagram	Graph	Hand gestures
The word *discharging*	Circuit diagram	Graph	Hand gestures

METHOD

Participants

This research involved two groups of participants from the University of Malta: Electrical Engineering Year 2 (N = 37) and Design and Technology Postgraduate teachers (N = 7). The engineering group was fully representative of its year in the university undergraduate programme. The Design and Technology sample of postgraduate teachers was selected as a convenience sample and was not representative. These groups were selected because the nature of the research necessitated involving individuals who had already experienced higher-level tuition in the field of electrical circuits, more specifically on the topic of resistor-capacitor series circuits.

Experimental Design and Procedure

This article reports only part of the outcome of a larger research project that focused on participants' perspicacity regarding basic resistor-capacitor series circuits. Figure 1 illustrates the overall data gathering structure of the larger research project. The shaded boxes indicate how the data collection process reported in this article fits into the context of the larger project. This article analyses qualitatively the responses of participants for one major category of the overall measuring instrument, the *Graph Given* category for the pre-test problem solving exercise. The sections that follow provide details about the methodological components pertinent to this article.

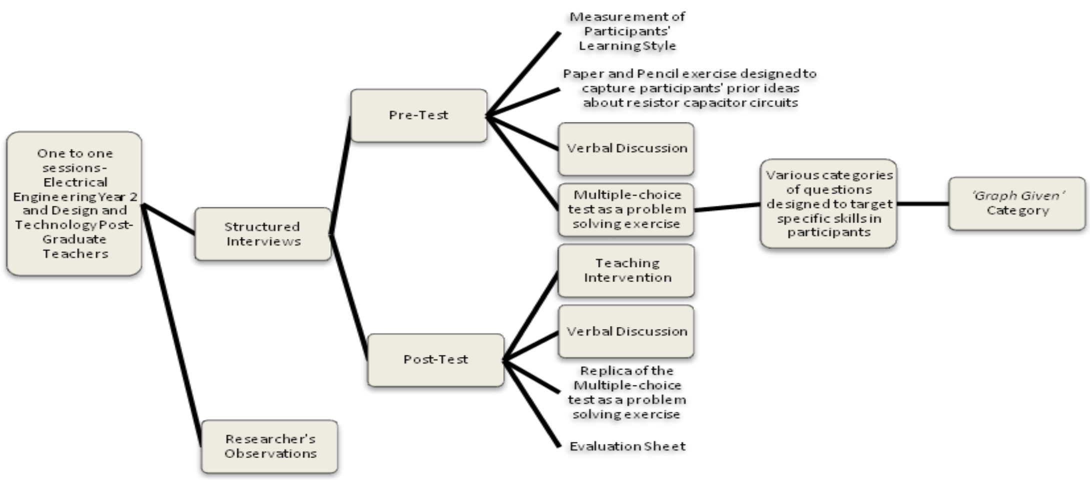

Figure 1: The main divisions of the structured interview for the individual sessions.

The Structured Interview

For all groups, the data gathering methods were conducted on a one to one basis with each participant. The structured interview was administered in two sessions, the pre-test and the post-test, each of approximately two hours' duration. During the pre-test session, participants were asked to work on the multiple choice test items. While problem solving, the participants were encouraged to think aloud and voice comments about the circuits in question. They were engaged in conversation and led into exploring their own reactions, and possible reasons for them, when particular salient circuits appeared on a laptop screen. Discussion of the quantitative aspect, the teaching intervention and the post-test is not within the scope of this article.

Verbal Discussion

The scope of the research was to explore the participant's approach to thinking about the function within the circuits, rather than conducting an assessment of the participant's knowledge. The participant was encouraged to comment freely on any aspect of each question during the tests, expressing one's problem-solving process, one's feelings and confidence levels throughout the exercise. Some participants needed to be prompted to generate a discussion while others conversed more spontaneously. The discussion was important in order to establish a trusting relationship between interviewer and interviewee. It made the research process seem less of an assessment and offered more involvement on the participant's part. This encouraged the participant to be more motivated towards the generation of a rich discussion.

The *Graph Given* Category

The questions in the category labelled *Graph Given* were designed to prompt discussion. Table 11 in Appendix A lists the circuits in the *Graph Given* category together with their corresponding graphs provided and question numbers as assigned for the pre-test and post-test. A sample of these questions as they appeared in the test is given in Appendix B. Each of these questions presents a situation where the switch is dynamic and the series resistor-capacitor circuit is engaged in two different paths that force a change in state of the circuit.

The questions start by guiding the participant to reflect about the capacitor in the circuit given, asking about the state this would be in, charged or discharged, when the circuit settles down after the switch was flicked. Consequently, the question presented the correct graphical response, which would be observed if one had to measure the voltage at node B with respect to electrical ground. The participant was then asked to comment if he/she agreed that the graph correctly represented the voltage level at node B with respect to electrical ground. These questions probed if participants always tended to associate the words *charge* or *discharge* with particular graphical shapes, irrespective of the circuit connections and the initial state of the circuit.

Analysing the Transcripts

The first step in the analysis of the transcripts was to read the data thoroughly until the researcher acquired sufficient familiarity with each interview. Consequently, the discussions pertaining to the questions classified under the *Graph Given* category were grouped together per question. Both pre-test and post-test discussions were included for every question involved. Because of this re-organisation of the data, the researcher could search for patterns and key comments pertaining to every question in the *Graph Given* category, both for the pre-test and the post-test.

ANALYSIS

Researcher's Hypothesis about the Participants' Performance

The researcher entered the interview and data analysis processes having the hypotheses listed in Table 2.

Table 2: Researcher's hypotheses.

Hypothesis 1	Most participants would tend to have preconceived ideas regarding the shapes of graphs associated with the output of particular circuits. More specifically, it was hypothesised that participants would tend to always associate the graph shape of Figure 2 with the charging of a capacitor and the graph shape of Figure 3 with the discharging of a capacitor, irrespective of the configuration of the circuit.
Hypothesis 2	Because of Hypothesis 1, participants would experience conflict when they encountered circuit situations, which challenged their pre-conceived ideas about circuit behaviour and corresponding output graph shape.
Hypothesis 3	Most participants would not be aware that for some particular circuit configurations given, the output voltage could rise above, or fall below the voltage range of the ideal voltage source given in the problem.

On analysing the transcripts, supporting evidence for the above three hypotheses was searched.

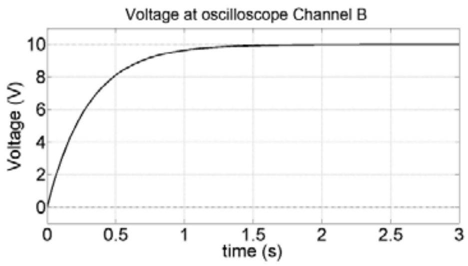

Figure 2: Exponential graph associated with the charging of a capacitor.

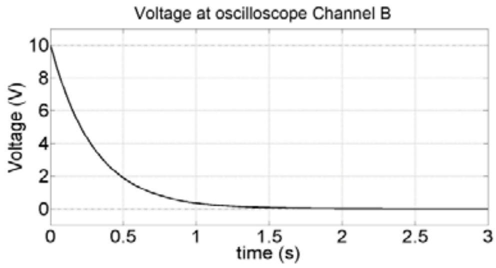

Figure 3: Exponential graph associated with the discharging of a capacitor.

Participants' Preconceptions of Graph Shape Associated with State of the Circuit; Addressing Hypothesis 1 and 2.

As already stated in Hypothesis 1 and Hypothesis 2, it was conjectured that most participants would tend to have biases regarding the shapes of graphs associated with the output of particular circuits and would consequently experience conflict if they happened to encounter situations, which challenged their preconceived ideas. More specifically, it was hypothesised that for Cases 1, 4 and 6 of Table 11, participants would find no conflict between the information deduced from the circuit schematic and that deduced from the corresponding graphs, which correctly represent the dynamics of the voltage potential required in the question. These were the cases where it was expected that most participants would find that the given graph complemented their reasoning about the behaviour of the circuit as deduced from the circuit schematic. For all the other questions listed in Table 11, it was expected that most participants would experience a conflict between the information about the circuit behaviour gathered from the circuit schematic, and that gathered from the corresponding graph.

Findings

Analysis of the interview transcripts revealed that for Cases 1, 4 and 6 in Table 11, most participants responded with quick, short, decisive answers indicating that they were confident that their answers were correct and did not need any deliberation whatsoever. Most of the answers given in response to these questions were single word or single phrase answers featuring the words: *charging*, *discharging* or *the graph complements my reasoning*. Most participants took very little time to reach a conclusion about the behaviour of the circuit in the cases of 1, 4 and 6 in Table 11. On the other hand, for Cases 2, 3, 5, 7 and 8, in Table 11, most participants took time to reflect carefully before reaching and submitting an answer. More often than not, participants engaged in a monologue or a discussion with the interviewer. In these cases the first thing most participants did was re-read the question or ask the interviewer to re-confirm what the question stated, as if to make sure that their understanding of the information provided was correct.

Once the correctness of the information was confirmed, participants proceeded towards a phase of active thinking, whereby, they voiced their reasoning about the problem aloud. Their discourse usually started by re-stating the problem and considering the circuit schematic or the graph separately, in order to reach a first conclusion. Consequently, they considered the other representation given, graph or circuit schematic respectively, and reached a second conclusion. In their final comments, the participants proposed arguments that disclosed their perplexed thoughts or their confusion in not succeeding to make ends meet. The participants spent much longer deliberating on Cases 2, 3, 5, 7 and 8 than on Cases of 1, 4 and 6 in Table 11.

The excerpts in Table 3 are a sample of participants' comments while tackling Cases 2, 3, 5 and 8 of the pre-test. Table 4 lists a discussion between the interviewer and the interviewee on Case 2 of the pre-test. These samples were selected for discussion here because they were considered the most representative of other participants' reactions to the same questions. A detailed discussion of these excerpts follows since such reasoning was found to be typical of participants. The underlined phrases were found to be the key evidence, which provides support for Hypothesis 1 and Hypothesis 2.

Consider the comment made by participant 10 for Case 5. This participant stated clearly that, in his mind, *going up means charging*, where, by *going up*, the graph of Figure 2 is understood. For this participant, the graph shape of Figure 2 is mentally tagged with the word *charging* and the functional event of charging the capacitor in the electrical circuit.

This same participant admits to gathering a different kind of information when perusing the circuit schematic. The participant states that on consideration of the circuit schematic, he deduced that the functional state of the capacitor would be discharging. The participant chose to weigh the information deduced from the circuit schematic more than that deduced from the graph because he stated that, eventually, he used the circuit schematic to reach a conclusion.

Hinging on this decision, he then goes back to the graph to re-interpret it and admits that he *knows* or infers, that the graph concords with the circuit schematic only because of his observation of the numbers on the y-axis of the graph, which range from a minimum of minus 10 V to a maximum of zero Volts. His inference that the circuit state as represented from the graph matches the circuit state as represented in the circuit schematic was a two-step process, which went through and depended on his observation of a numerical scale, rather than a more insightful interpretation of the graphical representation as related to the circuit behaviour. Reference to the full transcript for this same participant shows that his responses for Cases 1, 4 and 6, not shown in this article, were confident, concise and precise, indicating that his thinking process was not as elaborate as for Case 5 or that he may have recalled the answers for these questions by rote.

Participant 45 was so perplexed at seeing the circuit in Case 2 combined with its given corresponding graph that, to him, such circuit behaviour was *impossible*. On consideration of the circuit schematic, this participant correctly inferred the states, which the circuit was made to go through, *discharged and then charged*. On analysis of the graph properties, since from a maximum of 10 V, the graph decreased to zero Volts, he labelled this graph shape as being *a discharge graph*, thus, associating the particular graph curvature with the word *discharge* as a verbal tag and referent description for this graph shape. This self-made label did not match with his previous conclusion about circuit behaviour and he, therefore, decided that he was not in agreement with the graph. Like participant 10, participant 45 chose to weigh the information given from the circuit schematic more than that given by the graphical representation. Participant 10 adopted a similar problem-solving strategy for Case 3. On analysing the circuit schematic, participant 10 was convinced that the capacitor charged. When looking at the corresponding given graph, he described its shape as being *the opposite of charging*, hence, logically, in contrast to his previous deductions. He, therefore, concluded that it would be better not to use the graph to solve the problem since he feared that this would negatively affect his focus on his reasoning process. Once again, participant 10 chose to weigh the information given from the circuit schematic more than that gathered from the graphical representation, to the ultimate extent of discarding the graphical representation completely. Participant 10 reconfirmed this decision in his analysis of Case 8, whereby, he stated once again that *the graph disrupts me, it would be better if it were not given.* Such a problem-solving strategy and consequential feelings were shared by participant 04 for Case 3, who decided that he was *not even going to pay attention to the graph. I* [He] *would only focus on the circuit*.

The conversation between the interviewer and the interviewee in Table 4 is an example of how the researcher tried to guide the participants through such conflicting thoughts in the pre-test, by helping them to analyse the situation systematically, and articulate clearly their experiences. In order to acquire information from the participant, questions rather than statements were used more often. Here, it must be stated that although every effort was made not to influence the participants' response by using leading questions, at times it was found necessary to help the participant articulate one's perplexities by suggesting key words upon which the conversation could continue. It was observed that when faced with a situation, which they could not explain verbally, participants most commonly reverted to the use of gestures or the sketching of diagrams to communicate. Since, in this study, video capturing facilities were not used to record the data, it was felt necessary to help participants articulate better their verbal explanations. This could be regarded as a limitation of this study because one could argue that the participants were led into their thinking or use of particular modes of expression.

Nevertheless, one must consider that all participants were Maltese, and English was not their primary language. Therefore, eloquent expression using English technical jargon may have been a challenge for some. Note that the Maltese language has no equivalent of English technical jargon, such as the words *charging* or *discharging*, and even if most interviews were conducted in Maltese, English expressions for describing the behaviour of circuits were still used.

Table 3: Quotations that support the argument that the student is biased to thinking that charging and discharging should have a specific shape when it comes to the graphs expected.

Participant code	Pre-test question number	Participant's comment
10	Q55 Case 5	*I looked at the graph, and I saw that it goes up. And I know that, in my mind, going up means charging, so, I asked myself, why is it going up? But then I said to myself, …I know that it's discharging, when I saw the circuit, I know that it's discharging, so eventually I concluded from the circuit. When I look at the graph, I know it's discharging because I'm looking at the numbers [the y-axis], but I prefer to look at the circuit. When I see the circuit, I immediately know that it's discharging.*
45	Q58 Case 2	*...from node B to C. It's impossible! Here it was discharged and then it charged. It was 10 V and it started going down, down, down to zero. This is a discharge graph. The capacitor is charging. No, I do not agree with the graph.*

10	Q62 Case 3	*I will now use it* [the graph] *to try to complement my thinking. But it's not the source of my thinking. For me the capacitor charged, and I'm simply going to check it out. I reason it solely from the circuit, … it charged. I know that the graph is the opposite of charging, … so it's better if I don't use it, because normally when I focus on something, then I will change my reasoning.*
04	Q62 Case 3	*Q62 …* [reads]. *Discharged, charged. So, from the circuit I am saying that it charged. The graph is telling me that it discharged, but I know that it charged. I'm not even going to pay attention to the graph. I will focus on the circuit.*
10	Q65 Case 8	*The graph disrupts me, it would be better if it were not given. I would simply have said discharged, and that's it. In this case, it has confirmed that it discharged, but I still prefer that it would not be given. If I needed to use it in a more complex problem, it would disturb me even more. Here I know that I have just one voltmeter, or oscilloscope and it's ok. In the case where I would have a lot of readings, I would have to remember that that's the voltage BG, ...it would be better if it were not there.*

Table 4: Interviewer-Interviewee (04) conversation on question Q58 (Case 2) of the pre-test.

Interviewee	Interviewer
Ehm, …I concluded this to be charging no? So, well, wait a minute wait a minute, …this, from the graph, it's telling me that it's discharging! Heq?!	
	Don't start to doubt yourself now.
But isn't this discharging, …from 10 to zero, as time goes by?!	
	All I'm going to tell you is that, that, is a graph having that particular shape. Now, to interpret it as charging or discharging, …you need to be very careful. That's why I asked you where did you look at first - circuit or graph?
Circuit, circuit.	
	And from the circuit you concluded that it was…?
Charging.	
	Charging, ok. So now, when you see the graph, with that particular shape, is the graph challenging your previous conclusion?
Yes.	
	So you perceive a mismatch between the information given to you by the circuit and that given to you by the graph?
Yes, they don't match. I don't know! The graph is telling me that it's discharging, but the circuit no.	
	So what the graph tells you conflicts with what the circuit tells you?
Exactly.	

Discussion

The theme discussed in this section supports Hypotheses 1 and 2. Participants tend to associate the graph shape of Figure 2 with the word *charging* and the functional event of charging a capacitor. They also associate the graph shape of Figure 3 with the word *discharging* and the functional event of discharging a capacitor. In doing so, they restrict their analytic focus of the circuit towards the capacitor only, rather than considering the relationship of voltage potentials for the circuit holistically. This limits their analytic insight for other circuits, so much so, that they experience conflict when this strict visual-verbal association is challenged.

When conflict arises between the information participants gather from a circuit schematic and that gathered from a graphical representation, they tend to weigh the information gathered from the circuit schematic more, and use such representation to make their conclusions about the circuit's behaviour. This preferential choice towards the circuit schematic can be strong enough for them to refuse to consider the graphical representation as a possible aid towards the interpretation of the behaviour of the circuit.

Indeed, during the pre-test, some participants took such drastic measures as requesting a piece of rough paper to hide the graphical representation completely from view while they reasoned out the solution from the circuit schematic only. It was only during the post-test, and after a teaching intervention that these participants used both circuit schematic and graphical representation together to reach a conclusion for the circuit's behaviour. The conversation in Table 5 supports this claim.

Table 5: Interviewer-Interviewee (01) conversation on question Q55 (Case 5) of the post-test.

Interviewee	Interviewer
	Now do you remember last time in Session 1 you were hiding the graphs with a piece of paper because you said it's better for you if you just look at the circuit.
Now, no ...I'm using both circuit and graph. I can feel it.	
	And last time you said sometimes you had a conflict. Is that feeling of conflict still there?
No, now I feel that when I look at it, I don't want to consider the graph, because I don't like them, but it may be best to take information and understand from both representations.	

Participants' Awareness of *Out Of Range* Voltage Levels; Addressing Hypothesis 3

This theme provides evidence that supports the conjecture in Hypothesis 3, that the lack of awareness on the participants' behalf for some particular circuit configurations given, that the output voltage could go beyond the range of the voltage source given in the circuit. More specifically, for the circuits in Cases 5 and 8, that the voltage potential on node B with respect to electrical ground would momentarily go beyond the zero to 10 voltage range. Indeed, for the circuit in Case 5, the voltage of node B as measured with respect to the electrical ground point momentarily measures minus 10 V, while the same node for the circuit in Case 8 momentarily measures plus 20 V. This phenomenon is due to the behaviour of the capacitor when this is subjected to signals of high rate of change, such as the switching signals used in this study.

FINDINGS

The conversations between the interviewer and the interviewee in Table 6, Table 7, Table 8, Table 9 and Table 10 are typical of participants' reactions for Cases 5 and 8 and, provide supporting evidence for Hypothesis 3. Consider the discussion about Case 5 in Table 6. Participant 04 correctly identified the state of the circuit as being discharged by looking at the circuit schematic. Nevertheless, he was very puzzled by the y-axis of the corresponding graph. At first, by looking at the graph, he referred to the given curve and, thinking aloud, asked himself if the graph c*harged to 10 V*. It seems that at first glance, participant 04 perceived only the shape attribute of the curve and by its resemblance to Figure 2, jumped to the conclusion that this curve should mean that a capacitor is charging. The shape attribute of the given curve seemed to momentarily dominate over the numerical values given on its y-axis, which, a moment later, compelled the participant to reconsider his reasoning.

On re-evaluation of his own reasoning, and a second, more careful observation of the graph, participant 04 needed confirmation from the interviewer that the graph indeed spanned the vertical negative plane. When he was offered reassurance about this fact, he was puzzled to find out that the voltage potentials described by the graph were not included in the range specified by the given voltage source. In fact, pointing to the symbol of the 10 V voltage source on the circuit schematic, he insisted that in this source, *you have nothing minus 10, you have nothing below ground*. In his representation of the circuit, the given voltage source could not supply negative voltages and, therefore, negative voltages could not possibly exist within this circuit system. Since the given corresponding graph described the behaviour of the circuit in terms of negative voltages, participant 04 was quite perplexed.

Table 6: Interviewer-Interviewee (04) conversation on question Q55 (Case 5) of the pre-test.

Interviewee	Interviewer
Q55 …[reads]. *The capacitor has …discharged. …Wait a bit, wait a bit. Hasn't this* [pointing to the graph] *charged to 10 V, the capacitor? How come here there is minus 10?*	
	You try to find a reason.
I don't know if when you swap the capacitor and you put it up there, and you put the resistor down here, if it makes a difference. As yet, I worked it out that it makes no difference. But now that I am seeing this, …heq so? But isn't minus 10 below ground?	
	Minus 10 is below ground.
But here [indicating battery] *you have nothing minus 10, you have nothing below ground.*	
	No.
So how come minus 10?! [Participant seems very puzzled at this point].	

Similar reactions can be found in Table 7, Table 8, Table 9 and Table 10 for Case 8, for which the corresponding graph included a peak voltage level of 20 V, which once again was out of the level range, which the given voltage source could supply. From the discussion in Table 7, it is clear that participant 44, was knowledgeable about the state the circuit would take, and also about the expected graph shape corresponding to this state. Nevertheless, he was confused by the voltage levels involved. The overall shape of the corresponding graph for Case 8 is very similar to that in Figure 3 but is seen to peak at 20 V, and decrease to 10 V, instead of decreasing from 10 V to zero Volts. This happens because the initial voltage across the capacitor is equal to that of the voltage source, that is, 10 V, and the switching action causes the voltage level at node B to rise beyond the 10 V level, by another 10 V. Therefore, the 20 V level occurs due to an effective vectorial summation of the dynamic behaviour of node B, to the initial condition across the capacitor. It is the state of the circuit before switching that causes node B to rise up beyond the 10 V level. Participant 44 seemed to miss this fact from his reasoning. Expecting that the resultant graph shape should *start from 10* and *shift its axis down* to look exactly like the graph in Figure 3 (as he drew in rough), participant 44 revealed that he was not taking the initial condition of the circuit into consideration. Once again, the dominant feature, which was perceived and recognised as the state of *discharge* from the graphical representation, was the feature of curve shape only. The reasoning behind the participant's solution to the problem seemed to lack a thorough understanding of how to link and apply the feature of curve shape to other variables significant to the solution of the problem, such as the initial condition. Other participants have experienced very similar dilemmas when considering Case 8, as can be seen from the discussions of Table 8, Table 9 and Table 10.

Table 7: Interviewer-Interviewee (44) conversation on question Q65 (Case 8) of the pre-test.

Interviewee	Interviewer
Q65 ...A. For the graph, I'm not sure. I'm not sure but maybe it's correct.	
	How are you reasoning it out, ...from the circuit?
Because you have, ...mmm, ...it's this 20 here that is confusing me.	
	Do you agree with the shape of the graph?
With the shape yes.	
	So the problem is with the y-axis?
Yes, why it started from 20.	
	And where do you expect it should start from?
I expect it to start from 10. So the shape needs to shift its axis down.	
	So as a comment I could say that you think that the graph shape is all right, but, the y-axis no, because of the 20V?
Yes, exactly.	
	So, you'd expect the graph to start from 10? Would you draw for me exactly what you expect?
[Participant draws the graph he expects on scrap paper. It looks like Figure 3]. *Yes, it should start from 10. Now, this will not be exactly zero, on discharge.*	
	Well, ok, that happens theoretically at infinity time, or after a very long time.

Table 8: Interviewer-Interviewee (01) conversation on question Q65 (Case 8) of the pre-test.

Interviewee	Interviewer
Q65 ...Capacitor is in series, it is charging, it reaches the peak. Now, here there is a problem.	
	Why?
Because there is the 20 V. I think that it's discharging, but I'm not sure about this one.	

Table 9: Interviewer-Interviewee (04) conversation on question Q65 (Case 8) of the pre-test.

Interviewee	Interviewer
So this, when it started discharging, it went up to 20 V? Is that possible? That's, that's what you're telling me, no? When it started discharging, it went up to 20 V. How is that possible?!	
	Yes, you could interpret it in that way.
Humph! …I don't know, I don't understand. For me, this is discharged, from the circuit.	

Table 10: Interviewer-Interviewee (43) conversation on question Q65 (Case 8) of the pre-test.

Interviewee	Interviewer
Q65 ... I find the graph conflicting. Discharge, but I find the graph conflicting. The fact that it is 20. But at the back of my mind I think I'm wrong. I think it may be possible for it to reach that voltage.	

DISCUSSION

This theme has provided evidence to support Hypothesis 3. Participants may have identified the state of the circuit correctly from the information gathered through the circuit schematic, but they still misinterpreted the changes in voltage potentials expected from the circuit and resisted to accept that some circuit phenomena indeed challenged their preconceived ideas considerably. This theme has also shown that participants failed to consider all pertinent variables when analysing circuits. In the problems presented for this study, careful attention for the state of the initial condition of the circuit was a particularly significant variable of which to take note. Many participants failed to take this into consideration. All this has direct impact on participants' performance, especially during practical work, since their preconceived ideas may be strong enough as to limit their observational skills and openness of mind to unexpected scientific phenomena.

CONCLUSIONS AND IMPLICATIONS FOR INSTRUCTION

In line with the claims of dual coding theory, and following what was proposed in a prior study by [12], this study has revealed that students are developing links across visual-verbal study material. These links may be forming quite unconsciously, and this unawareness may paradoxically limit their skills for the transfer of knowledge. The outcome of this study has indicated that the participants possessed the predisposition to invariably associate the word *charging* with the graphical representation of Figure 2 and the word *discharging* with the graphical representation of Figure 3. This referential association seems to be as strongly implanted as a paired associate mental representation that participants' experience conflict when the outcome of a resistor-capacitor series circuit does not conform to this fixed pattern. Because of this mental inflexibility and inability to apply the conceptual knowledge involved, participants have not been capable of transferring their prior knowledge of the subject matter to unfamiliar cases. The implications for instructions indicate that the problem may lie beyond the fact that students find the interpretation of graphical representations difficult. The source of this problem may also lie in the repeated emphasis that teaching methods or instructional materials give to just one circuit situation, namely Cases 1 and 6 in Table 11. It seems that instead of being interpreted as examples, which illustrate a more overarching concept, these cases are taken to be the primary and unique way in which a resistor-capacitor circuit may function. This has a negative impact on students' capacity for the analysis and design of electrical circuits.

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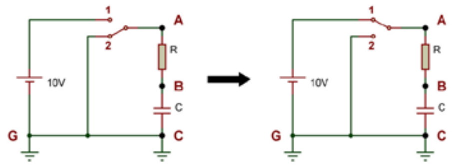
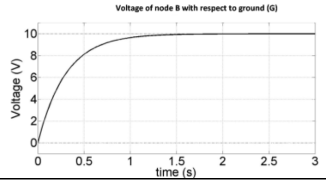
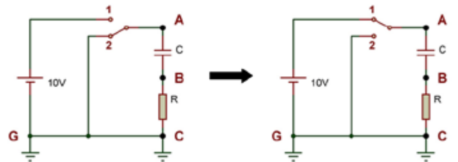
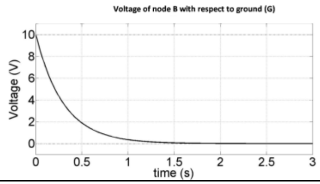
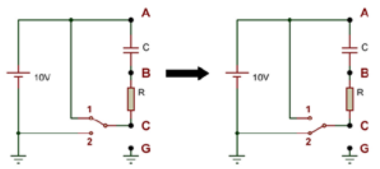
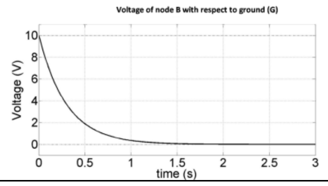
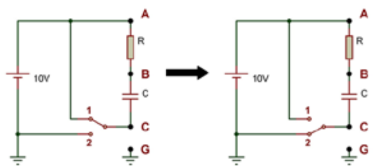
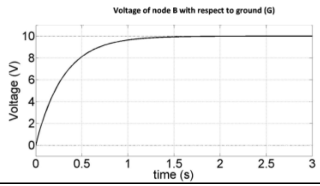
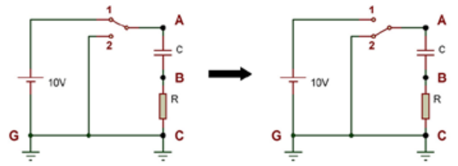
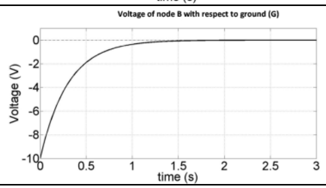
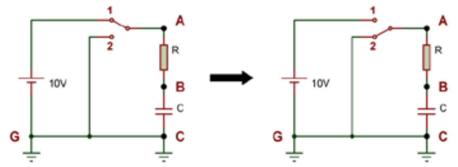
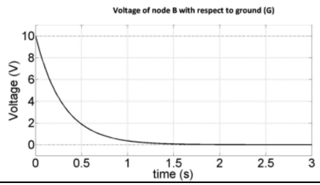
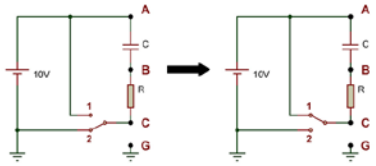
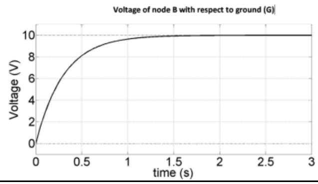
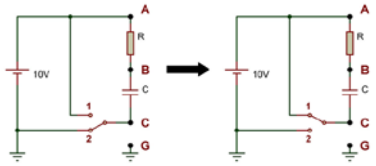
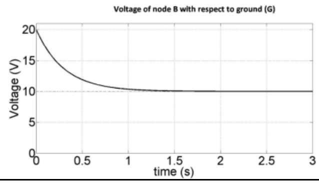
BIOGRAPHY

Sarah Pulé received a BEng (Hons) in Electrical Engineering and, subsequently, a Postgraduate Certificate in Education from the University of Malta in 1998 and 1999, respectively. She served for one year as a teacher at the Convent of the Sacred Heart School, St. Julian's, teaching physics, integrated science and information technology at secondary level. Later, during her four-year employment as a laboratory officer in the Department of Power and Control in the Faculty of Engineering at the University of Malta, she started work at conducting research in the field of modern intelligent automatic control of robots achieved by the use of neural networks. She was successful in gaining an MPhil in the field in November 2005 and was employed as a full-time assistant lecturer teaching electronics and control systems at the Faculty of Education in 2004 within the Department of Mathematics, Science and Technical Education. Currently, she is reading for a PhD in design and technology education with the University of Loughborough, UK. She was also appointed by MATSEC as an examiner and moderator for the science and technology section of the Systems of Knowledge matriculation certificate for four years. Her interests lie in researching innovative methodologies to deliver higher order technical processes to students, who may not have a rigorous engineering and mathematical background. From June 2003 to 2011, she held the position of director on the Water Services and, thereafter, EneMalta Board of Directors, appointed by Dr Austin Gatt, Minister for Industry, Information Technology and Investments.

APPENDIX A

Table 11: Eight cases of a resistor-capacitor series circuit used in the *Graph Given* category.

	Case no.	Circuit Path	Graph Shape	Pre-Test question no.	Post-Test question no.
Charging Paths	1			Q54	Q32
	2			Q58	Q36
	3			Q62	Q40
	4			Q63	Q41
Discharging Paths	5			Q55	Q33
	6			Q57	Q35

	7			Q64	Q42
	8			Q65	Q43

APPENDIX B

The two circuits below show the flicking over of a switch performed by an experimenter. The switch is first put in position 2 and left there for a long time. When the switch is flicked over from position 2 to position 1 as shown in the circuits below, the graph shown is observed on an oscilloscope when measuring the voltage of node B with respect to ground (G). In this case, the capacitor has:

□ A. Charged.
□ B. Discharged.