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Spatial cognitive processes involved in electronic circuit interpretation and translation: their use as powerful pedagogical tools within an education scenario

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Abstract

While there is much research concerning the interpretation of diagrams such as geographical maps and networks for information systems, there is very little on the diagrams involved in electrical and electronic engineering. Such research is important not only because it supports arguments made for other types of diagrams but also because it informs on the cognitive processes going on while learning electrical and electronic engineering domains, which are generally considered difficult to teach and learn. Such insight is useful to have as a pedagogical tool for teachers. It might also benefit would be self-learners, entrepreneurs, and hobbyists in the field because it can guide self-learning practices. When cognitive practices specific to this knowledge domain are more understood, they might give rise to automated intelligent tutor systems which could be used to augment teaching and learning practices in the education of electrical and electronic engineering. This research analyses the spatial cognitive processes involved in the translation of an electronic circuit schematic diagram into an iconic representation of the same circuit. The work shows that the cognitive affordances of proximity and paths perceived from a circuit schematic diagram have great influence on the design of an iconic diagram, or assembly diagram, representing a topologically equivalent electronic circuit. Such cognitive affordances reflect and affect thought and can be used as powerful pedagogical tools within an educational scenario.

Keywords

Electronics engineering education, circuit schematic and assembly diagram, design and technology, cognitive processes, spatial thinking, visual analysis.

Introduction

Schematic diagrammatic representations in the field of electrical and electronic engineering have much in common with diagrams in information systems design in that they represent the abstract entity of electricity and its flow through components with specific behaviours. An electrical circuit schematic is defined by its structure, and the typical behaviour of the components within it. Overall structure and individual behaviours give rise to the function which the circuit is designed to accomplish (de Kleer, 1979, 1984; de Kleer & Brown, 1983). Electronic circuit schematics also represent the presence of real physical components and the connectivity networks between these components, often called a netlist. As such, they can be translated into other diagrammatic representations more suited for the physical assembly of an electronic circuit, or indeed directly onto a real assembly without the need for translation. In prototypic work on electronic circuits within an educational scenario it is typical to use physical tools such as breadboards and copper stripboards to implement the circuits for testing. Experts or experienced electronics personnel can usually assemble an electronic circuit directly from a schematic diagram without the need for a mediating diagrammatic representation. Novice students in electronics engineering or non-experts, like assembly line workers, may need a mediating diagrammatic representation to aid the proper assembly of an electronic circuit since reading directly from a schematic diagram involves a significant amount of knowledge and also a significant cognitive load.

This research investigates the design behaviours of novice students in electronics engineering when asked to translate an electronic circuit schematic diagram into an iconic assembly diagram using specific software. The research does not exemplify how well the students understood the abstract circuit function, but only their design decisions when translating between representational diagrams. The aim of this work is to:

1. Investigate how novices interpret a circuit schematic diagram and relate this to the creation of a corresponding iconic diagram, which eventually would lead to a real functional circuit;
2. Discover error patterns which may occur when they translate between electronic schematic diagrams and electronic iconic diagrams. This could facilitate and hasten fault finding practices within an educational setting since both teachers and students would know what to look for when checking circuits; and
3. Inform pedagogical practices in the electrical and electronic engineering domains.

Accomplishment of these aims is targeted at the concern that the content of electronics topics is poorly represented in the learning process in general, not only within the area of design and technology and engineering, but also within other science subjects such as robotics, physics, and computer science (Rihtaršič, Stanislav, & Slavco, 2016). Recent research suggests that although electronics education could be considered as one of the key linkages within STEM/STEAM education, it is often neglected (Kocijancic, 2018).

The features of electrical and electronic schematic diagrams

Early depictions of electrical circuits emphasized the visual appearance of components. The diagrams had an iconic nature because the level of realism within the illustrations focused on the appearance of the objects within the circuit. By the year 1900, symbols were developed for electronic components and the nature of the diagrams shifted over to being more schematic in nature (Hegarty, Carpenter, & Just, 1996). The salient change of perspective from iconic diagrams to schematic diagrams is that the graphic symbols and organisation of these do not primarily represent the physical positions of objects, but the functional features of their electrical connectivity (Gregory, 1970). The conventions developed for schematic circuit diagrams indicate both the type of components and their connectivity network. Hence, schematic circuit diagrams are external representations which convey concepts that are inherently spatial as well as others which are metaphorically spatial. Although symbols play an extremely important role in the transfer of information through schematic circuit diagrams, they are not the only important elements in the process of recognising diagrams. A large number of unorganised circuit components as well as their mutual position in the whole circuit structure may significantly impede the transition of information via circuit diagrams (Pudlowski, 1988).

The primary focus of schematic electronic circuit diagrams is to depict both abstract concepts and physical realistic objects. An example of an electronic schematic diagram is shown in Figure 1. The circuit in Figure 1 is also that which will be analysed further for the scope of this research.

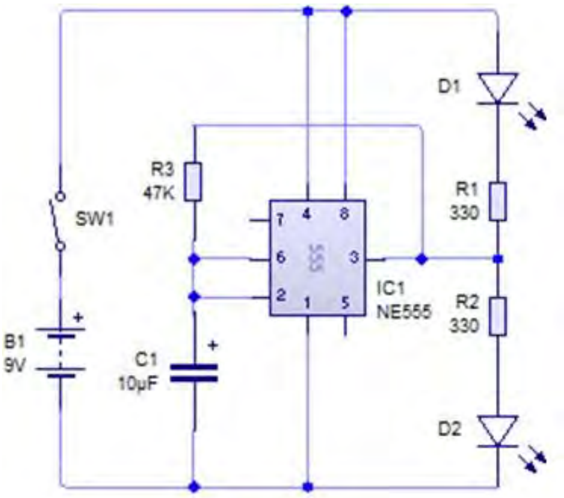

Figure 1: Schematic diagram of an electronic circuit having the function of a timer

Generating a topologically equivalent electronic circuit assembly diagram

The context of this research takes place within an educational scenario whose intent was to teach some practices within the domain of electronics engineering. One of the practices involves the translation of an electronic schematic diagram into a real prototype circuit. This can be done in a variety of methods, but for the scope of reaching the intended educational learning outcomes, it was required that the prototype circuit be implemented on a stripboard. A stripboard is a thin, rigid wafer with copper strips and holes on which the real circuit components may be soldered. The educational learning outcome required that the practical implementation of the prototype circuit is preceded by a software implementation that would enable the makers to plan, visualize and test the end product before making it. To this end, the software called Fritzing^{TM} (Knöring, Wettach, & Cohen, 2009; Wettach et al., 2007) was used. Fritzing is an electronic circuit prototype planner aid. With such software the maker can select electronic components from a parts bin, place them on the stripboard and connect them accordingly. When clicked, these iconic representations also reveal the corresponding symbolic schematic representations of the electronic components. Figure 2 gives a snapshot of how the iconic representation of a stripboard (Figure 2a) and the parts bin (Figure 2b) appear in Fritzing software.

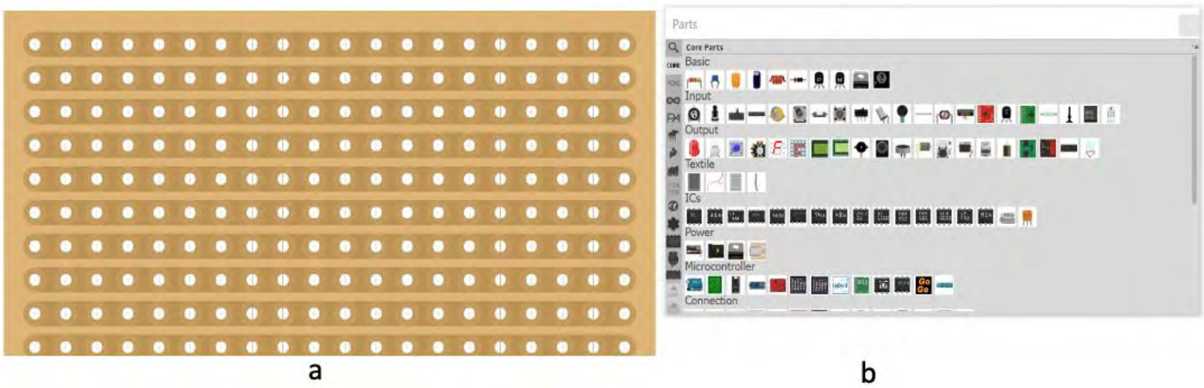

Figure 2. Fritzing^{TM} interface showing copper stripboard and parts bin

Prior research on the representation of circuits through diagrams

In most past studies on electrical circuit diagrams, the representation of the electrical circuit was conveyed via a circuit schematic employing standard symbols or through a verbal description of the circuit. Studies such as that of Engelhardt and Beichner (2004) also employed realistic displays of circuits. A global view of all schematic circuit diagrams in most of the past studies gives the impression that, within any one of these, authors do not seem to employ a deliberately designed method of positioning the electrical symbols of the schematic with respect to a common framework, such as a vertical or horizontal organization of the circuit diagram. Although experts in the field of electronics normally do employ such a technique for drawing standard circuit diagrams, they might do so quite unconsciously drawing on experience rather than through conscious design (Marshall, 2008).

In electrical circuits, it is the topological connections that matter most and not the geometry of the schematic diagram. Nevertheless, even if this may only be a cognitive aid rather than a necessity, the way an electrical circuit is drawn may impinge on the cognitive load necessary to envision the function of the circuit (Amigues, Cazalet, & Gonet, 1987; Beeson, 1977; Caillot, 1985; de Kleer & Brown, 1983; Johsua & Dupin, 1985; Marshall, 2008; Pudlowski, 1988).

Cognitive processes involved in translating an electronics schematic diagram into its iconic counterpart

Highly specialized abstract content, like electrical circuit diagrams, impose challenging processing demands because the presence of higher order relationships in these scientific diagrams seems not to be readily apparent (Lowe, 1988, 1989a, 1989b, 1990, 1994, 1995). Novices in a field seem to benefit from diagrams whose significant attributes are made to *stand out* or *go together*, thus highlighting meaningful visuo-spatial relationships within the diagram and guiding attentional shifts by the very structure of the data (Egan & Schwartz, 1979; Grant & Spivey, 2003; Larkin & Simon, 1987; Lowe, 1994; Pule' & McCardle, 2010). Indeed, the management of the perceptual properties of a diagram was found to be key to generating insight in problem solving tasks and increasing significantly the frequency of correct solutions (Grant & Spivey, 2003). This may be achieved by controlling the relative dominance and perceptual precedence of a graphic object within a diagram. By manipulating attributes such as relative size, protuberance, minima of curvature, isolation, strength of boundaries and colour, the reader may be directed to shift his/her attention towards particular salient graphic objects in a diagram earlier or later when the diagram is perused (Hoffman & Singh, 1997; Winn, 1991). Thus, the pre-attentive organization of information by means of what Winn defines as *configuration* and *discrimination*[1] has direct implications on cognition and learning, and the way in which perceptual groups are formed largely determines how the information in a diagram is encoded (Winn, 1991). Significant affordances which a page can offer include the attributes of proximity, position and paths. Proximity and use of space augments topological information with Euclidean space by categorizing subsystems in clearly defined perceptual groups. Position is normally divided into the horizontal and vertical directions, each metaphorically representing entities such as time, actual spatial position or abstract concepts. Paths are usually used to indicate real or metaphoric connectedness and relationships (Crilly, Blackwell, & Clarkson, 2006; Nickerson, Corter, Tversky, Zahner, & Rho, 2008). It is noteworthy to mention that, since these perceptual processes are pre-attentive and organize the data directly, they should not be affected by the reader's characteristic content knowledge.

One potential source of difficulty with interpreting a diagram-based representational format may lie in the perceptual cues offered by the representation (Kaplan & Simon, 1990). Perceptual features, such as structure, allow inferences to the function of a representation, and may form perceptual-functional units, or affordances. The perceiving of function typically entails observing or knowing about elements in action or interaction, what de Kleer and Brown (1983, p. 156) call *'envisioning'*. With experience, people can come to make functional inference from perceptual form and appearance (Tversky, 2005).

Physical and Cultural Experiences

When a diagram is used to represent abstract concepts, the metaphorical mappings of the diagram's structure are usually based on our physical and cultural experiences. These may have become so internalized that we grow unaware of them. The conditions for our experiences depend on constraints such as the three-dimensional space in which we live. Thus, for example, our immediate space is constrained by a local upright direction determined by the Earth's gravitational field and a flat, solid surface, orthogonal to the local upright direction, which bounds our immediate space from below. This gives rise to the spatial orientational metaphor such as the up-down dimension which is ubiquitous and salient in the structuring of our perceptions, cognitive maps or verbal descriptions. The upward direction dominates the downward direction since things above ground are more accessible (Blackwell, 1997; Boroditsky, 2000; Lakoff & Johnson, 1980; Shepard & Hurwitz, 1984). Another experiential constraint is the structure of the language we use to communicate. For example, the direction of writing horizontally from left to right in Western languages is usually used to express temporal sequence (Nickerson et al., 2008; Tversky, Kugelmass, & Winter, 1991). Considering these constraints together therefore, it is not surprising to note that we tend to read diagrams from left to right, top to bottom (Winn, 1991). Such mechanisms which were primarily developed for perceiving and reasoning about the spatial world are likely to be used for reasoning about other domains, for example electrical voltage potential, due to the interaction of representations in the mind and on the page. Due to their experiential basis, such metaphors prove to be very powerful when employed in search processes as applied to diagrams

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[1] Configuration processes: objects or concepts which appear to form clusters, the sequences in which objects are processed and which objects later receive the most attention. Discrimination processes: how objects and processes are shown and the ease with which one object can be distinguished from another.

(Nickerson et al., 2008; Stenning & Oberlander, 1995; Winn, 1993). Humans are attuned to constraints in their physical environment and may benefit from a visual representation which limits abstraction (Blackwell, 1997; Kirsh, 2010; Stenning & Oberlander, 1995). By employing graphical constraining, the coupling between the elements in the visual display and the represented world becomes more tractable and supportive for the generation of inferences (Scaife & Rogers, 1996).

The Components of Device Knowledge

Kieras (1988) lists several kinds of knowledge people may have about devices, among which (a) the purpose for which it is used, (b) how to operate the device, (c) its inputs, outputs and connections, (d) its internal and external layout and appearance, (e) the functional relationship between its inputs and outputs, (f) procedures for maintenance and (g) its internal structure and mechanisms, that is, how it works.

These different kinds of knowledge about devices serve different purposes. Kieras (1988) argues that in the domain of electronic systems, knowledge which leads to inference strategies is usually not made explicit in training materials. It seems that the trainee is expected to pick these up by himself from examples in the training materials or during apprenticeship. This is not easy for a novice learner. The knowledge types (a) to (g) listed above lie on an increasing difficulty hierarchical scale, whereby inferring how a device works is exceedingly more difficult than, for example, understanding the purpose for which it is used, or how to operate it.

Most knowledge possessed by novices seems to be related to operating the device as opposed to explaining how it works. Even a task such as the maintenance of an electronics circuit may not involve knowing the design considerations behind the discrete component level, but only the identification of the malfunctioning components. For the purposes of this research, the type of device knowledge required was more of a procedural nature. Participants needed to know how to read and interpret the input and output connections of electronic devices, lay out the iconic appearance of the devices and ensure that the connectivity between them results in a functional circuit.

Circuit Schematic Diagram Representation and Interpretation – Chunking and Topological Influences

The work of Egan and Schwartz (1979) and Geiselman, Wickens, and Samet (1983) explores memory for symbolic electrical circuit diagrams and procedural knowledge respectively. The main outcome of this work is that skilled electrical technicians, that is experts in the field, recalled circuit diagrams by chunks of functional units, where symmetry in the diagram seemed to play an important role. This contrasted with novices who recalled the circuits on the basis of spatial proximity alone. This outcome has influenced the way circuit diagram was drawn in this research. The circuit was perceptually chunked to make it easier for participants to arrive at the salient functional units.

Intellectual Growth

Kosslyn (1980) states that during the imagery process a subject needs to first generate the image and inspect it, then consequently maintain it in memory and manipulate it. Mental representations are abstractions and by their very nature simplify and inevitably distort information (Tversky, 2015). There are a multitude of possible mental transformations such as orientation, change of location, reconfiguration and rearrangements in length, width area, proportion etc. Many of such mental transformations appear to be internalizations of physical transformations. Things can be known only by the way humans have organized them perceptually and conceptually (Dusek, 2006; Guyer & Wood, 1998).

The topology of a system is typically embedded in the Euclidean plane and it is very difficult to avoid being influenced by the spatial features of a diagram. Visuospatial cues or their absence can have deleterious effects on people's interpretations of diagrams. This might lead to predictable biases and errors. Errors on isomorphic diagrams can probably be accurately predicted by deriving some salient spatial features of a model diagram (Corter, Nickerson, Rho, Tversky, & Zahner, 2009).

From an educational perspective, Bruner (1966, p. 5) states that '*intellectual growth is characterized by increasing independence of response from the immediate nature of the stimulus*'. Bruner claims that much of what the learner does is predictable from the knowledge of the stimuli that are impinging upon him at the time he responds or just prior to that time. A great deal of growth is present when the learner is able to maintain an invariant response in the face of changing states of the stimulating environment, or when he learns to alter his response in the presence of an unchanging stimulus environment. Bruner maintains that growth also depends upon internalizing events into a storage system that corresponds to the environment. It is this system that makes possible the learner's increasing ability to go beyond the information encountered on a single occasion. He does this by making predictions and extrapolations from his stored model of the world. Most importantly, intellectual development is marked by an increasing capacity to deal with several alternatives simultaneously, to tend to several sequences during the same period of time, and to allocate time and attention in a manner appropriate to these multiple demands.

According to Bruner, the structure of any domain of knowledge may be characterized in three ways: a) the mode of representation in which it is put, b) its economy and c) its effective power. Any idea, problem or body of knowledge can be presented in a form simple enough for any learner to understand it in a recognizable form. However, mode, economy and power vary in relation to different ages, to different styles among learners, and to different subject matters. Bruner maintains that any domain of knowledge can be represented in three ways:

1. By *enactive* representation. This type of representation is a set of actions appropriate for achieving a certain result. Bodies of knowledge can be known without having imagery or words to describe them. Such bodies of knowledge are very hard to teach to anybody by means of words or pictures and most often their transmission is based upon the learning of responses or forms of habituation.
2. By *iconic* representation. Iconic representation is primarily governed by principles of economical transformations in perceptual organizations. This type of representation is a set of visual or other sensory organization, usually dependent upon images or graphics which summarize and stand for a concept.
3. By *symbolic* representation. This type of representation is a set of symbolic or logical propositions drawn from a symbolic system that is governed by rules or laws for forming and transforming propositions. Symbols are arbitrary; there may be no analogy between

> the symbol and the object it represents. Symbolic systems provide the means of getting free of the immediate appearance of an object as the sole basis of judgement and usually, such as in the example of mathematical equations, offer the attribute of compactibility.

Actions, images and symbols vary in difficulty and utility for people of different ages, different backgrounds and different styles. Moreover, each of these can be context specific.

Besides the mode of representation, (Bruner, 1966) maintains that economy and power are also important features of the structure of knowledge representations. Economy in representing a domain of knowledge relates to the amount of information that must be held in mind and processed to achieve comprehension. The more items of information one must carry to understand or deal with a problem, and the more successive steps one must take to process information to achieve a conclusion, the less the economy. Economy varies with mode of representation and is also a function of the sequence in which material is presented or the way it is learned. Economy can be further increased by using diagrammatic notations. In addition, there may be varying degrees of economy within such recourse to the iconic mode of representation. Bruner gives an example featuring information about intercity flights, where the task is to determine the shortest distance from one city to another. He explains how different representations, in the form of: a) word list in random sequential order; b) word list in alphabetical order; c) a topological graph diagram with vertices standing for city names, and lines standing for the interconnection in between them; and d) a re-arranged topological graph diagram describe the information given. The economy and hence, effective power of utilization of each of these representations varied dramatically due to the way the information was presented. Bruner states that a structure may be economical and powerless, but it is rare for a powerful structuring technique in any field to be uneconomical. He relates this to the canon of parsimony shared by many scientists, that nature is simple, and only when nature can be made reasonably simple can it be understood. According to Bruner, the power of a representation can also be described as its capacity, in user terms, for connecting matters that, on the surface seem quite separate.

Bruner claims that apart from the mode of representation, and its economy and power, sequence of instruction is also key to effective learning. He states that the sequence in which a learner encounters materials within a domain of knowledge affects the difficulty he will have in achieving mastery. There is no unique sequence for all learners, and the optimum in any particular case will depend upon a variety of factors, including past learning, stage of development, nature of the material and individual differences. Bruner’s key assertion about sequence is that if the usual course of intellectual development moves from enactive through iconic to symbolic representations of the world, it is likely that an optimum sequence will progress in the same direction. This is considered a conservative doctrine. For, when the learner has a well-developed symbolic system, it may be possible to circumvent the first two stages. The problem with this is that the learner may not possess the imagery to fall back on when his symbolic transformations fail to achieve during the act of problem solving.

Method

This research first involved the choice of a circuit function and the planning of a circuit schematic diagram suitable for the context of a design and technology or vocational engineering technology class at secondary school level in Malta. This choice was based on the subject's curriculum for the award of a Level 3 qualification on the Malta Qualifications framework (MQF, 2010). To minimize bias within the generation and analysis of the data, two researchers worked independently and took two separate roles. One researcher was responsible for the planning and collection of data, while the other solely for its analysis. The second researcher was not involved in the selection of the circuit, the planning of its schematic representation or the administration of the exercise to participants. This ensured that the second researcher, who was an expert in electronics, was completely estranged as to what circuit configuration to expect and could not form preconceptions of how the circuit "should" look like from her personal mental imagery collection of electronic circuit schematics and assembly forms. It is well known that experts and novices in diverse domains such as physics, mathematics, computer programming and design organise, process and represent information differently from novices (Adelson, 1984; Chi, Feltovich, & Glaser, 1981; Larkin, McDermott, Simon, & Simon, 1980; Novick, 1988; Schoenfeld & Herrmann, 1982). Research shows that experts perceive problems by means of deep abstract solution-oriented structures and categorize and index problems differently from novices. According to (Mervis, Johnson, & Scott, 1993) experts can notice and base their solutions on subtle perceptual attributes and their correlated functional affordances much more than novices. Indeed, they claim that expert performance is rooted in perception and that perceptual features may be integral to expert solutions. The lack of participation of the expert in the planning and data collection made sure that her influence on the other researcher and on the novice students would be null.

The participants were taken from a class following the subject of vocational engineering technology in a local Maltese secondary school. The class was a mixed gender, mixed ethnicity (majority European, minority Asian and African), classroom with ages ranging between fifteen and sixteen. The number of participants was eighteen (n=18) students. This sample was a convenience sample since the collection of data needed to coincide with the point in time when project work on electronic circuit assembly was being conducted by the class teacher as part of the normal curriculum. The participants were simply defined by that particular class who happened to be in the phase of circuit assembly during the time window available for the researchers to obtain access and collect data. Since the task was part of a normal lesson where schoolwork and homework was assigned and expected from students, the participants were not offered any rewards. The sample cannot be considered as representative of a wider population unless the research is repeated. The participants were given the circuit schematic diagram shown in Figure 1 and asked to translate it into a stripboard layout using the software Fritzing^{TM}. Such an exercise constituted part of the normal curricular work and was not accompanied by any textual explanations of the circuit. Participants presented their work as digital images showing a populated iconic circuit representation similar to Figure 7.

The analysis of the data was mainly qualitative and performed by taking a grounded theory approach since concepts were seen to emerge from the data by induction. The first step involved the scrutiny of the circuit schematic form and the extraction of its own features in an absolute way by an expert in electronics. Such features, if present, were hypothesized to influence participants' iconic designs. Consequently, the expert could form an initial personal hypothesis of how the novice participants could have potentially organised their circuit assembly.

The second step was to analyse participants' iconic diagrams to qualitatively search for any patterns. The analysis of the iconic diagrams commenced by human observation and comparison of the Fritzing software diagrams to the schematic circuit diagram which they were given to translate. The observations primarily searched the data for the retention of the topological equivalence of schematic and iconic circuit representations, however, the repeated instances of proximity, order and perceptual chunking were soon very readily evident while going through the data. These were the concepts arrived at by the process of induction and which could possibly be applicable to domains other than electronics and thus generalisable within a broader spectrum of design, technology and engineering education.

Results and Analysis

Analysis of the circuit schematic diagram in Figure 1 – results presented by the expert

The manipulation of visual images may reduce the load on working memory and speed up the process of inference (Scaife & Rogers, 1996). Human abilities to recognize information are highly sensitive to the exact form in which the information is presented to the senses and rearranging the elements of a particular representation may cause it to correspond to a different possible world (Larkin & Simon, 1987; Pudlowski, 1988; Stenning & Oberlander, 1995). If a circuit schematic is displayed to students and structured in a way that its components are arranged freely, it may lead to misinterpretation of the circuit's meaning and consequently confusion regarding its important functions. One aspect to consider when drawing circuit schematics is the mutual proportion of elements composing the entire figure. Appropriate proportions in terms of measurements and distribution of elements and lengths and angles between them may have a decisive meaning in the process of perception. When drawing a circuit schematic, it was found ideal to have a certain proportional relationship between the elements resulting in a degree of geometrical harmony (Pudlowski, 1988). The circuit in question was analysed for its conceptual affordances of paths, proximity and position (Nickerson et al., 2013).

The circuit in Figure 1 is an astable multivibrator with two functional sub-circuit chunks. The first, referred to as the LED path, is the closed loop path which includes the 9 V battery; the single pole single throw switch, SW1; the upper LED, D1; the resistor R1; the resistor R2 and the lower LED D2 which returns to the negative terminal of the battery. Figure 3 shows this as a path affording enclosure. The block diagram of the same path in Figure 4 shows that this path has one bifurcation at the connection between resistor R1 and R2 leading on to pin 3 of the integrated circuit (i.c.).

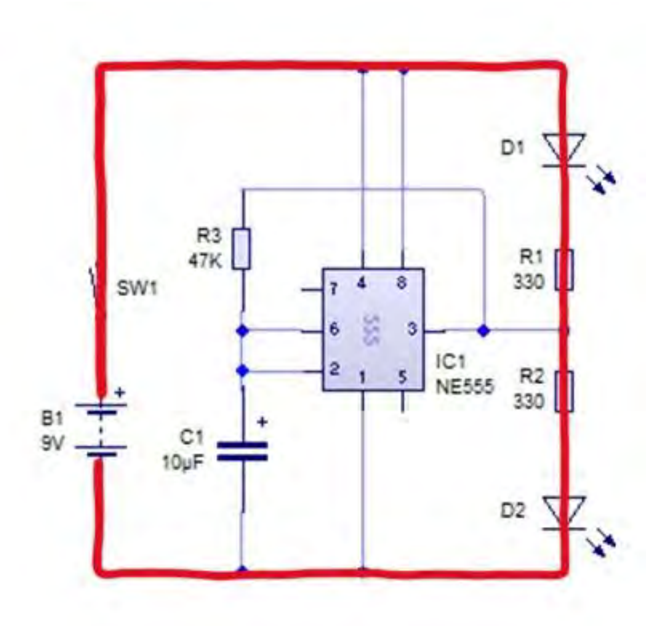

Figure 3: LED path on schematic diagram

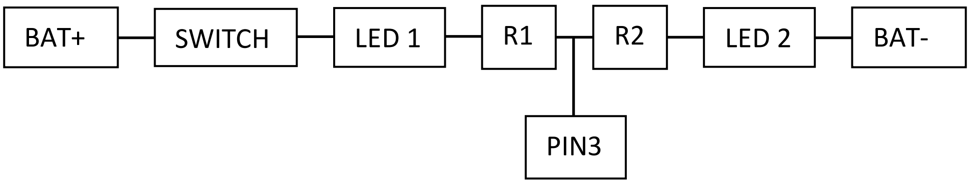

Figure 4: LED path as a block diagram

The other functional sub-circuit chunk is part of the charging-discharging path, referred to as the RC path: from pin 3 of the integrated circuit to resistor R3 to capacitor C1 and to the negative terminal of the battery which can be considered to be the ground point of the circuit. This is shown in Figure 5, where clearly, there is no enclosure afforded. Its corresponding block diagram, Figure 6, shows that in between resistor R3 and capacitor C1, there are two bifurcations leading to pin 2 and pin 6 of the integrated circuit.

The perceptual nature of these paths already suggests that the RC path might offer greater cognitive challenges than the LED path.

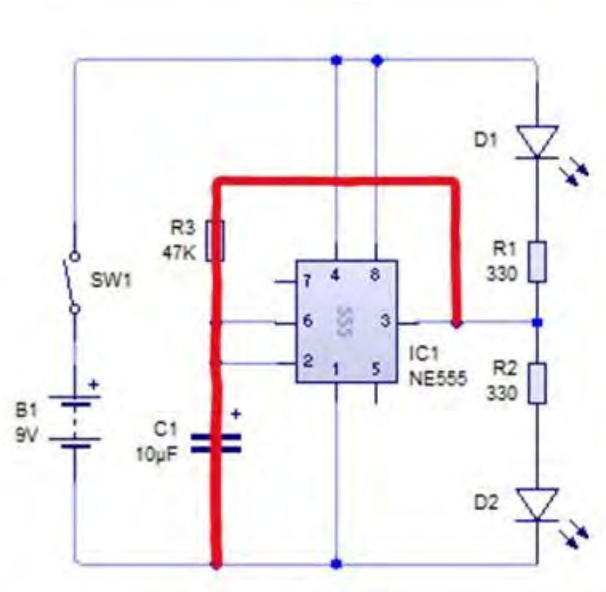

Figure 5: The RC charging-discharging path

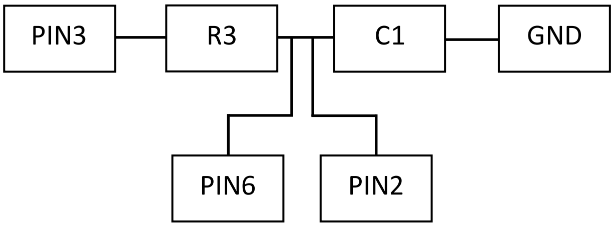

Figure 6: The RC path as a block diagram

Results and Analysis emanating from participants' iconic circuit representations

Results and analysis for the iconic representations of Figure 1

The analysis of the iconic representations was divided into two sections. The first section focused on the positioning of key components or related sub-chunks with respect to a Euclidean grid and with respect to each other. The second section of the analysis focused on the continuity of the paths within the two main functional sub-circuit paths: a) the LED path and b) the resistor-capacitor (RC) path. Figure 7 shows one sample of the populated iconic representations which were analysed. Fritzing software retains the physical dimensions of all iconic instances as constant, hence automatically ensuring that the scale of the iconic representations is identical. Length measurements taken on the iconic representations were therefore taken with respect to a common scale.

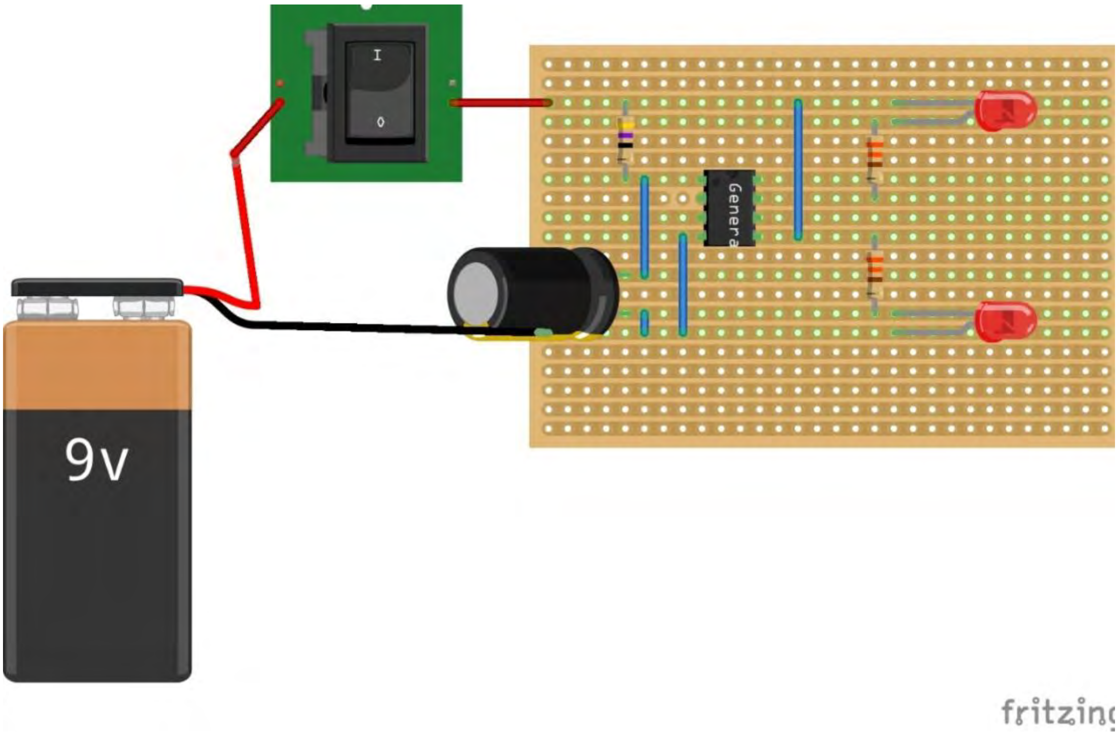

Figure 7: One sample of the populated iconic circuit representations on Fritzing gathered from participants

Section 1: Symbolic to Iconic representations

The electronic circuit schematic diagram was read correctly by all participants. All circuits presented in stripboard layout had the correct number of components on the board. All stripboard layouts also had the correct iconic representations corresponding to the circuit schematic symbols. Slight variety was only noticed as regards to the type of switch chosen (push button or toggle) and the type of capacitor chosen (ceramic type or electrolytic type). Both these choices had no significant effect on the functionality of the circuit. There were no instances of misinterpreted circuit schematic symbols.

Section 2: Stripboard Layout Proximity and Position of sub-circuit chunks

The proximity of the circuit symbols within the schematic diagram was measured by circumscribing the relevant path symbols with a circle and recording its diameter as shown in Figure 8. The ratio of the respective diameters on the circuit schematic given to participants was calculated as follows:

$$\frac{proximity\ of\ LEDs\ in\ schematic\ diagram}{proximity\ of\ RC\ in\ schematic\ diagram} = \frac{diameter\ of\ P_{LED}}{diameter\ of\ P_{RC}} = 1.6723$$

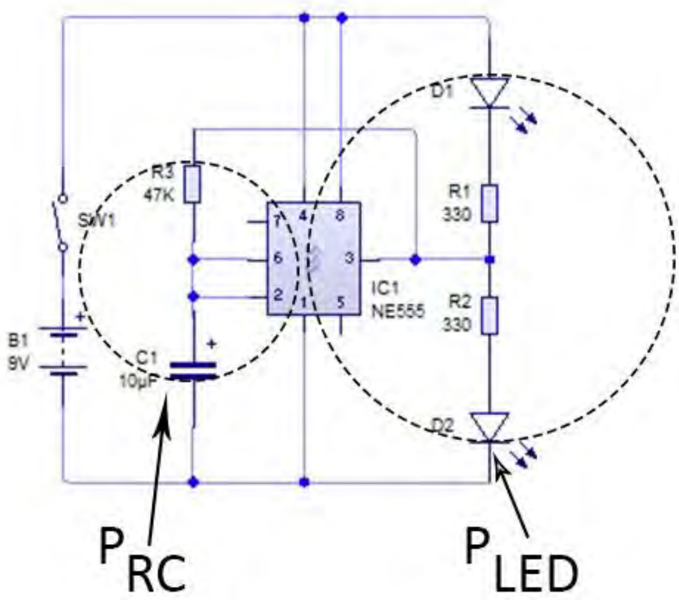

Figure 8: Measuring the proximity of components within the two main sub-chunks of the circuit schematic

The same was done for all stripboard layouts designed by the participants. The two main sub-chunks of the circuit on the stripboard layout of all participants were circumscribed by two circles and the ratio of the diameters was calculated. From the measurements on the stripboard layouts the average proximity of the paths is:

$$\frac{proximity\ of\ LEDs\ on\ stripboard\ layout}{proximity\ of\ RC\ on\ stripboard\ layout} = 1.6510$$

It is striking that the average ratio of proximity of components on the stripboard layout is so close to the ratio of proximity of components on the schematic diagram. It seems that participants perceived cognitive spatial measurements on the schematic diagram were transferred onto the stripboard layout design even if this was not required and did not affect the functionality of the circuit in any way. It seems that participants preferred to retain the spatial distances between circuit symbols and circuit iconic representations.

Such proximity indicates that the sub-chunks were readily recognized. It also acts to support research such as that of Egan and Schwartz (1979) who discovered that novices tend to chunk circuits according to a proximity criterion. Indeed, this phenomenon also resonates with the findings of (Piaget & Inhelder, 1956, 1971) whose research is more scientifically generalizable since it is about human development in general. In their work on the child's conception of space, Piaget and Inhelder suggest that within the first stages of development, proximity is more important than other factors of organisation, such as resemblance or symmetry. The findings that link so closely the proximity factor on the circuit schematic to the proximity factor on the iconic representations infer that participants are still in the initial phases of development of the knowledge domain in electronics education, which is indeed the case.

Section 3: Stripboard Layout Position, Order and Proximity of key components

This section focused on the positioning and order of key components or related sub-chunks with respect to a Euclidean grid and with respect to each other. By the first round of observation of the data, the researcher was able to extract patterns which were evident for the salient components of the circuit. These macro features were verbalised in qualitative statements which could be classified by the Boolean descriptors: “true” or “false”. The statements were classified for every iconic circuit representation collected from the participants. Consequently, the percentage of participants for which the respective statements were true was calculated from the summation of the responses.

Table 1: Method of coding the iconic diagrams for the layout and order of salient components

	Statement	True	False
1	The battery is positioned to the left of the stripboard.	☐	☐
2	The battery terminals are upwards (north facing).	☐	☐
3	The i.c. notch is upwards.	☐	☐
4	The strips of the stripboards are horizontal.	☐	☐
5	Both resistor and capacitor (RC path) are to the left of the i.c.	☐	☐
6	The resistor (RC path) is above the capacitor (not necessarily vertically aligned).	☐	☐
7	The resistor (RC path) is vertically aligned to the capacitor.	☐	☐
8	The LEDs are positioned to the right of the i.c.	☐	☐
9	The LEDs are vertically aligned to each other.	☐	☐

The battery

The majority (94.4%) of participants positioned the iconic image of the battery on the left side of the stripboard. The battery was positioned vertically with its terminals pointing upwards in 66.67% of the cases. Most participants who rotated the battery on its side positioned the positive terminal above the negative terminal.

The NE555 integrated chip

The position of the integrated chip was always central with respect to other components of the circuit. Indeed, the i.c. seemed to be regarded as the visual centre of mass of the circuit. Most participants (94.4%) positioned the i.c. with its notch in the upward position when the strips of the stripboard were horizontally aligned. Aligning the copper strips horizontally has a practical advantage and participants may have been purposefully instructed to always align the i.c. as such with respect to the copper strips. The advantage of this orientation lies in the fact that, in this position, fewer isolation cuts are necessary to prevent some of the i.c. pins from being shorted by the copper on the stripboard. Participants may have been alerted to this by their teacher and therefore the high rate of compliancy is probably biased by prior teaching interventions. This can be considered as a source of constraint (Kaplan & Simon, 1990).

The resistor-capacitor charging-discharging sub-chunk path

In 77.78% of the cases, participants positioned the 47kΩ resistor, R3, and the 10µF capacitor, C1, to the left of the NE555 integrated chip. In 72.22% of the cases, the resistor was positioned above the capacitor, while in 33.33% of participants aligned R3 vertically with respect to C1.

The LED sub-chunk path

The LEDs, D1 and D2, together with their respective series resistors R1 and R2, were positioned to the right of the NE555 integrated chip for 72.22% of the cases. Most participants (63.89%) aligned these components vertically to one another.

In their research (Kotovsky & Fallside, 1989) discovered that subjects tend to always adopt a suggested representation instead of choosing deliberately between different ones. According to (Tversky, 2015) there is various kinds of evidence which suggests that the mind attempts to align different experiences and modalities by selecting shared elements, identifying a frame for the elements and aligning the reference frames and elements. This entails cognitive sub-processes such as finding the critical elements, determining the appropriate reference frame and then aligning them.

Participants chose to imitate closely the schematic layout of the circuit when designing the iconic stripboard layout. This is typical of novice learners (Pudlowski, 1988, 1993). The layout is not just an imitation of the schematic but also conforms to the perceptual preferences which were discussed beforehand. Both schematic and iconic circuits conform to the dominant configuration of having the upper areas representing the 'dominant' positive power rail. Both schematic and iconic circuits conform to a left to right reading structure, which also happens to coincide with the implicit knowledge within the domain of electronics, of drawing inputs and source components on the left, the process components in the middle and the output components on the right as shown in the general system block diagram of Figure 9.

Figure 9. Implicit way of drawing systems

It is therefore clear that the spatial order, sequencing and even proximity of the symbols in the schematic diagram has greatly influenced the design of the iconic stripboard diagram. This is in support of the arguments emanating from the literature.

Section 4: Path analysis

This section of the analysis focused on the continuity of the paths within the three main functional sub-circuit paths: a) the LED path and b) the resistor capacitor (RC) path and c) the power rails. Qualitative statements describing the netlists of all paths were listed as in Table 2. The researcher classified the statements for each iconic representation presented by the participants.

Table 2: Statements describing netlist of the timer circuit of Figure 1

	Statement: The following path is connected correctly:	True	False
1	Pin 8 to supply (direct or after switch)	☐	☐
2	Pin 4 to supply (direct or after switch)	☐	☐
3	Pin 1 to ground	☐	☐
4	Pin 3 to resistor RC, to R3	☐	☐
5	Resistor RC (R3) to C	☐	☐
6	Capacitor to ground	☐	☐
7	Pin 6 to mid RC	☐	☐
8	Pin2 to mid RC	☐	☐
9	Battery positive to switch	☐	☐
10	Switch to LED D1	☐	☐
11	LED D1 to R1	☐	☐
12	R1 to R2	☐	☐
13	Pin 3 to mid R1 and R2	☐	☐
14	R2 to LED D2	☐	☐
15	LED D2 to ground or negative of battery	☐	☐

Connection of the i.c. to the power rails

The circuit required pin 8 and pin 4 of the integrated circuit to be connected to the positive terminal of the power supply, and pin 1 to the negative terminal of the power supply as shown in Figure 10. The results show that 77.78% of the participants connected pin 8 correctly to the positive rail, 61.11% connected pin 4 correctly to the positive rail, but only 50% connected pin 1 correctly to the negative rail. Taken collectively, the percentage of students who connected the power rails correctly was 62.96%.

It is of interest to note that there were instances where pin 1 was erroneously connected to the positive rail, while pin 4 was connected erroneously to the negative rail. Figure 11 shows the pins and their corresponding pin numbers of the iconic integrated circuit on the stripboard. Clearly pin 1 and pin 8 are symmetrical about the vertical plane, while pin 1 and pin 4 are symmetrical about the horizontal plane. When the pins were connected incorrectly, it seems that in such instances, the mind's valency for horizontal left-right symmetry (pin 1 with pin 8) or vertical directional asymmetry (Casasanto & Henetz, 2012) might have been the cause for the erroneous connections. The participants' reaction may be the result of the co-operation or competition between the two important features: one geometric and the other semantic (Van Sommers, 1984). In this case it seems that the geometric feature dominated the semantic feature resulting in an erroneous connection.

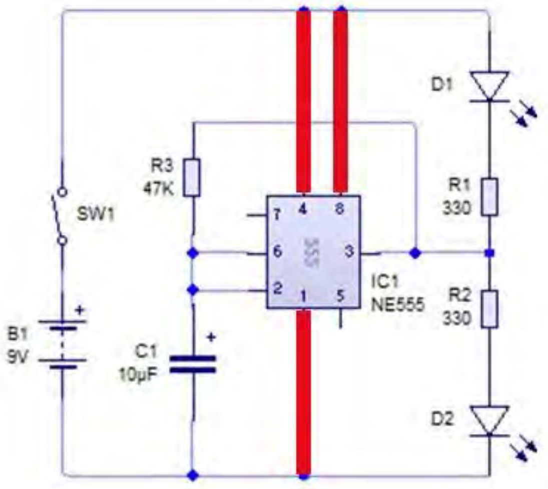

Figure 10: Power rails within the circuit schematic diagram

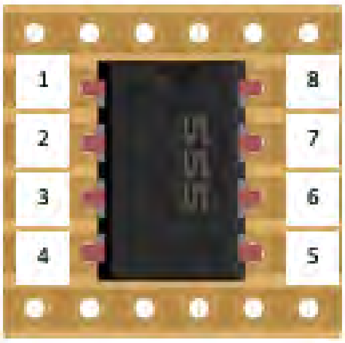

Figure 11: Iconic representation of the NE555 timer integrated circuit

Connections for the LED path

Table 3 shows the percentages of correct connections for each path in the netlist of the LED path. Considering that this path exhibits vertical symmetry about the point where resistor R1 meets resistor R2, connectivity errors for the upper half of the circuit were less than those for the lower half of the circuit. This seems to suggest that students were less confused when connecting the upper half of the path in question. When taken collectively, the percentage of students who connected the LED path correctly is 80.95%.

Table 3: Continuity breakdown of LED path

Connection	**Percentage of participants who connected the given paths correctly (n=18)**
Battery positive to switch	83.33%
Switch to LED named D1	94.44%
LED named D1 to resistor R1	88.89%
Resistor R1 to resistor R2	77.78%
Resistor R2 to LED named D2	50.00%
LED named D2 to negative terminal of battery or ground point.	77.78%

Connections for the RC path

Table 4 shows the percentages of correct connections for each path in the netlist of the RC path. The two paths with the least amount of connectivity errors are a) the path from resistor R3 to capacitor C1 and b) the path from capacitor C1 to ground. These paths are visually evident as vertical paths in the circuit schematic. The other three netlist paths within the RC path are seen to visually branch out at 90 degrees from the main vertical stem. This vertical stem can be considered as the “line of action”, (Hegarty et al., 1996, p. 664), connecting the resistor to the capacitor. All three branching sub-paths which do not lie within the line of action exhibit a greater amount of connectivity errors from participants. Taken collectively, the percentage of students who connected the RC path correctly is 53.33%.

Table 4: Continuity breakdown of the RC path

Connection	**Percentage of participants who connected the given paths correctly (n=18)**
Pin 3 to resistor R3	50.00%
Resistor R3 to capacitor C1	55.56%
Capacitor C1 to negative terminal of battery or ground point.	77.78%
Pin 6 to mid-point of R3-C1	38.89%
Pin 2 to mid-point of R3-C1	44.44%

It is possible that participants have used a prior learnt structure, such as a sequential chain, to understand concepts and make inferences for circuits in electrical and electronics engineering. This would be rather natural since electricity always flows in closed loops and this is what is taught in any physics or engineering class. Research about concepts in electricity highlight common dominant misconceptions brought about by sequential reasoning and sequential biases (Duit, Jung, & von Rhoneck, 1984; Taylor & Tversky, 1992). It is therefore not surprising that the path which was connected most correctly was the LED path (80.95%), rather than the power rails (62.96%) or the RC path (53.33%). The LED path is the only path out of the three that perceptually affords a closed loop structure and that has components which can be seen to be positioned in a spatial clockwise succession, offering enclosure of the other components. Out of all three paths, the LED path is the one that appeals most to primitive cognitive processes which are probably deeply rooted into the participants’ cognitive abilities. The power rails afford a degree of symmetry about the horizontal plane and seems to have afforded medium difficulty of interpretation. The RC path is cognitively the most taxing since its flow involves a reverse reading order from right to left. Clearly, the novice participants still need to develop cognitive spatial skills to read, interpret and act, or possess “spraction” (Tversky, 2015), for those paths needing a greater cognitive load.

Limitations

The number of participants approached for this research is small and they were appointed only by convenience because that was permitted by ethical regulations governing the scope of this project. As such, the repeatability of the work cannot be claimed yet. The process of analysis for this research relied only on one human researcher who was experienced in electronics education and in teaching and the only one who accepted to act as analytic researcher. The analysis could benefit either by having more than one person analysing the data or else having the analysis automated through the use of image processing techniques and machine coding as in the work by Nickerson et al. (2013). This would make the analysis more objective and much more accurate and rich quantitative measurements and relations would be possible.

Discussion

This work has shown that the spatial features of a circuit schematic diagram have considerable influence on novices' performance on a would-be procedural task and are considered to be "powerful", by Bruner's definition. The stripboard was essentially a blank area which could have been populated in any way, if the electrical topological connections were retained as those for the schematic diagram. The electronic circuit function would still have been achieved with an iconic circuit assembly diagram that had nothing in common with the schematic diagram other than the topological relations. Indeed, when experts plan the assembly of a real circuit, there are usually other variables which need to be taken into account such as ease of maintenance procedures, access to salient connections for measurement purposes, heat dissipation, economy of space due to cost of production etc. The design variables which should govern the planning of an electronic circuit assembly diagram go beyond the topological connections present within the schematic. It is clear that the novices who participated in this research were not yet taking into consideration such higher order variables in electronic circuit assembly practices but were fixated into the lower level cognitive processes related to the connectivity of the circuit. The novices who participated in this research have yet to develop their intellectual growth of the domain.

It is also evident that careful design and awareness of the spatial features of a circuit schematic diagram could significantly aid pedagogical practices in the domain of electrical and electronics engineering. Different diagrams serve different roles and novices in a knowledge domain should be made aware of which design variables are best served by a diagram in question. An electronic circuit schematic diagram serves the role of representing the structure, behaviour and function of the circuit, but does not infer information about its physical attributes and possible causes of malfunction due to poor choices within the layout of the physical components. Thus, a circuit schematic diagram supports conceptual knowledge while a circuit assembly diagram supports procedural knowledge. The usual pedagogical sequence of presenting electronic circuits representations in a typical engineering class starts from the symbolic and goes to the iconic. This sequence is in reverse of what Bruner recommends and might explain the learners' difficulty encountered when translating between diagrammatic representations. Further research would be needed to determine an optimised pedagogical strategy to minimise such difficulties, however it would seem to be reasonable to conclude that the visuo-spatial design of an electronic circuit schematic diagram has considerable influence on novice learners. Powerful and economical design strategies that target proximity, paths and placement of electronic symbols together with evident chunking and easily perceptible lines of action can be powerful pedagogical tools to adopt within an electronic engineering class.

Although the main topic of this work focused on the assembly of one particular simple and common circuit, the outcomes of this study may prove useful for other technological domains at other levels of teaching and learning. In studies such as the ETL project with undergraduate engineering students (Entwistle, 2005; Entwistle, et al., 2005; Entwistle, Nisbet, & Bromage, 2005), it was noted that students were less likely to adopt a deep approach to learning during analogue electronics work than in other topics because the analysis of analogue circuits recurrently proved difficult for a substantial proportion of students. The key points identified as essential for supporting understanding were (a) interpreting circuit diagrams, (b) imagining circuit behaviour, and (c) using simplifying transforms. Using powerful and economical design strategies which target the "perceptual form" of the circuit schematic, could prove useful for adopting deep approaches to knowledge in analogue electronics at a higher level than presented in this study.

The suggestion for necessitating a deeper approach to knowledge naturally instigates enquiry into what processes may be involved in understanding that knowledge and being able to provide a scientific explanation when communicating it. Kolari and Savander-Ranne (2004) state that in understanding, the nature of knowledge and the pattern of associations between its elements is most important. Merely measuring the amount of knowledge is insufficient when seeking to estimate understanding. Indeed Johnson-Laird suggests that a measure of understanding a phenomenon involves knowing:

> *what causes it, what results from it, how to influence, control, instantiate or prevent it, how it relates to other states of affairs or how it resembles them, how to predict its onset and course, and what its internal or underlying structure is (Johnson-Laird, 1983, p. 2)*

The outcomes of this work suggest that chunking and easily perceptible lines of action within a circuit schematic diagram could help in identifying the sub-systems within a circuit and therefore could aid in the adoption of a systems approach to understanding how the circuit works. In the astable circuit of Figure 1 learners should be able to relate the flashing frequency of the LEDs to the resistor-capacitor sub-system chunk and its related time constant. The understanding of relation of knowledge could start at the perceptual form, go through the systems approach and end within the more general scientific concept of how, in physics terms, time is related to frequency, and which components are responsible for the control of frequency in this circuit, thus satisfying Johnson-Laird's measure of understanding. According to Ausubel (1975) modifications to cognitive structure can be accomplished through manipulations of pedagogical content and sequence which could lead to conceptual changes into the cognitive structures of the mind (Langley & Simon, 1981; Rumelhart & Norman, 1981; Thagard, 1990; Vosniadou, 1994). This could potentially be true to domains other than electronic engineering.

Accessing cognitive structures of learners in a visual way is especially relevant to most topics in design and technology and engineering since the proportion of visual learners is typically high (Felder, 1988). The organisation of perceptual form might not just be an aid for deeper understanding of knowledge but also be a way of communicating it better through scientific explanations rather than descriptions. Explanations can be defined as scientific if, apart from providing a feeling of understanding, they provide a theoretical framework for a given phenomenon, while integrating a range of related phenomena and thus going beyond the initial, original phenomenal impetus (Brewer, Chinn, & Samarapungavan, 1998). As discussed previously, the outcomes of this work show that it is most probable that the organisation of perceptual forms in a diagram might influence deep understanding of knowledge and consequently this would be reflected in how the learner communicates that knowledge. The methodology used in this work was largely dependent on visual analysis rather than verbal analysis of students' work due to the nature of the topic. It is conjectured that such visual analytic processes might be applicable for a range of other technological areas and contexts, especially those where the knowledge is visual or non-verbal. Such analytic methods might give precious insight into how visual and active learners (Felder, 1988) interpret knowledge and how to design research strategies and pedagogical practices for effective and efficient teaching of such learners.

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