European Journal of Education Studies
ISSN: 2501 - 1111
ISSN-L: 2501 - 1111
Available on-line at: www.oapub.org/edu

doi: 10.5281/zenodo.2575088
Volume 5 | Issue 11 | 2019

CONCEPTUAL CHANGE ON THE LEARNING JOURNEY: FOUR 'R'S FOR SUSTAINABLE LEARNING IN APPLIED CONTEXTS

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Abstract:
Developing abstract conceptual knowledge is often problematic for learners because the phenomenon of interest cannot be observed. Knowledge is a product of learned theories and the outcome of learners' practice. Through practice, such as the modelling and simulating of abstract phenomena, learners translate representations, for example diagrams and schematics into other forms such as physical models. Through this process conceptual change in the learner's knowledge schema develops understanding and expertise enabling its application in new situations. This case study research explored learners' perceptions of change in understanding during a two year General Certificate of Secondary Education (GCSE) Design and Technology: Electronic Products course. The findings indicate that changes in conceptual understanding occur through the need to gradually engage with the practicalities of modelling and simulating the phenomena of interest. Learners were shown to adjust understanding from an initial theoretical focus, to a more pragmatic view of knowledge grounded in their own observations of simulated phenomena. Learners' dispositional attitudes to learning were found to support the nature of learning activities encountered during the period of the research. The discussion concludes with a model of sustainable learning based around the four 'R's: relate, reinterpret, reflect and revise. The model describes specific learner actions proposed as necessary in support of the development of cognitive skills and learning autonomy within a conceptual change view of learning.

Keywords: conceptual change, sustainable learning, learning journey, procedural knowledge, learning disposition

1. Introduction

Abstract concepts, such as those encountered in electronics education, can be difficult to develop because the phenomenon of interest cannot be observed; only the product of

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the phenomena may be readily observed. Voltage, current and resistance represent such phenomena and learners develop an understanding on the basis of both theoretical principles and practical experience. Gainsburg, Rodriguez-Lluesma and Bailey (2010) highlight this distinction, emphasising historically-based knowledge and the tacit knowledge gained through activities and procedures associated with problem solving. This view emphasises the situated nature of knowledge (Lave and Wenger, 1990) related to concept development in applied skills subjects such as Design and Technology and Engineering. The view however applies more widely and is applicable, for example, to the natural sciences more generally.

Theoretical principles nonetheless, gained through historically-based knowledge, are useful in communicating knowledge and have been described as providing the reference point for thinking about the behaviour of electricity (Metioui and Trudel, 2012). Conversely, it has been shown that appreciable understanding can be built upon the practical experience of developing electronic circuits and that these concepts are open to considerable interpretation (Twissell, 2018). Understanding in this way is developed following the principles of procedural knowledge (McCormick, 1997), rather than those of a more 'scientific', or knowledge as 'object' nature.

2. Literature Review

2.1 Constructivism and conceptual change

The relevance of procedure has been considered central to constructivist approaches to learning, such as those described by Bruner (1977) and Kolb (1984), where change in learners' understanding leads to the assimilation of new knowledge (Piaget, 1955). An important vehicle for scaffolding change in understanding is provided through the process of translating representations such as diagrams and models (Ainsworth, 2006). This translation, or reinterpretation process, provides the opportunity to view knowledge from different perspectives and can lead to conceptual change; that is change in the schema held as current understanding for the phenomena of interest. Learners thus modify their current personal understanding on the basis of experience, gradually integrating new knowledge into existing understandings (Chen, Pan, Sung and Chang, 2013). Here conceptual change theory (CCT) is used to define learning viewed in specific ways to CCT.

Chen et al.'s (2013) conceptual change model includes the following conditions which describe a learning trajectory: 1) learning material triggers dissatisfaction with existing understanding 2) new concept visualisations provide intelligibility 3) plausibility of concept is achieved when visualisation can be matched with theoretical understanding and 4) to overcome long standing misconceptions, visualisation needs to be linked with manipulation and exploitation opportunities. This approach represents a 'traditional' radical constructivist (von Glasersfeld, 1995) view of conceptual change. The view may however miss alternative explanations for change in understanding (Harrison and Treagust, 2001), and may therefore benefit from attention to learners' individual and social facets of learning (Duit and Treagust, 2010). Kural and Kocakulah

(2016) provide a useful analysis of this modification in perspective on conceptual change and discuss the emphasis on learners' motivational dispositions in particular as central facets of conceptual change.

2.2 The procedures and processes of learning

Learning through development and change in understanding can be viewed as a matter of choice in the learning strategy adopted by the learner. Bruner (1977) described his developmental taxonomy within a process of strategic learning episodes including: the acquisition of new knowledge (complementing existing knowledge), transformation (the new knowledge is manipulated, analysed and converted to another form) and evaluation (new knowledge is considered in context and checked for generalisations and plausibility). Reinterpretation is central to the taxonomy's application to development and learning. Kolb's (1984) experiential learning cycle provides the additional dimensions of active agency and reflection on action during the process of reinterpretation. This provides clarity on the procedural learning process and suggests specific strategies which have the potential to progress the learner from assimilation to the accommodation of understanding (Piaget, 1955).

Adopting this view of learning places as centrally important the agency and actions of the learner, rather than the educator's need to 'impart' knowledge (Knapper, 2006). The agency of the learner is often multi-faceted where a range of strategies are applied to suit the context (Siegler, 2005), as found by Twissell (2018) in relation to electronics concept formation. Actions are thus personal adaptations to problems grounded in experience and not the product of the widely promoted, but problematic, 'learning style' (Coffield, 2006) which implies a fixed view of learning potential. Thus adapting to problems in personal ways may reflect more about learners' dispositions for different approaches to learning and their preferences for different learning strategies.

2.3 Dispositions for learning

There is very little recent research explaining how learning dispositions, such as motivation or resilience, are perceived by learners to support their learning. The degree of action taken by learners has been considered to reflect an individual's level of personal efficacy; that is their ability to manage self-referential thoughts and to maintain achievement when faced with difficulty (Bandura, 1982). Personal efficacy may manifest itself in what can be termed a 'disposition' for learning. Costa and Kallick, (2002) describe sixteen 'habits of mind' that reflect the specific dispositions individuals apply when problem solving in the real world. Resnick (1999) suggests that a dispositional view of learning reflects an explicit strategy-based approach which develops learners' self-efficacy and eventual learning success. Kural and Kocakulah's (2016) view emphasises the dispositional dimension within a conceptual change approach to learning. Learning is therefore more sustainable for students who have consciously embraced and applied such personal strategies in the formation of abstract concepts.

Disposition development therefore aims to empower learners towards an awareness of conditions and strategies for success in learning and enhanced independence to complement the development of subject specific knowledge and skills. Lucas, Hanson and Claxton's (2014) Engineering Habits of Mind model includes three different levels at which this may occur including: a general level, a subject specific level and a core learner-character level. The research discussed in this paper focuses on the general institution-based dispositions including: ownership, courage, resilience, innovation and motivation. Participants in this research have therefore been exposed to an enhanced focus on these dispositions during the period of the research and consequently the research methodology embraces participants' views on their relevance.

The case study research discussed here sought to identify both learners' individual perceptions of change in understanding about abstract electronics concepts and the dispositions which may have contributed to such change. The discussion takes place within the context of secondary school GCSE Design and Technology: Electronic Products (UK). Previous research in this area has focused on the close observation of students within a 'natural' learning environment and identified learners' specific conceptions of electronics knowledge during a single phase in their learning (Twissell, 2018). Twissell (2018) identified four conceptual profiles including: the operative (understanding based in hands-on experience), the logician (understanding based in logic/digital electronics), the programmer (understanding based in programming) and the dialectic (understanding of both digital and analogue electronics) to describe the different ways learners engaged with the concept of analogue/digital voltage.

However although this provided a useful taxonomy of students' conceptual profiles, the nature of change in understanding and the influences on such change was not apparent. The research discussed here therefore sought to expose students' perceptions of the learning process within the context of the two year course of study. Students' experiences on the course, engagement with other learners and their perceived dispositions for learning grounded the conceptual framework for this study.

3. Methodology

This case study research aimed to explore change in students' understanding about electronics concepts as a development of Twissell's (2018) previous research which identified a taxonomy of four conceptual profiles (the operative, logician, programmer and dialectic), but not a trajectory of change. The research used a phased approach to data collection to enable an assessment of change in conceptual understanding to be made. The following two key questions were asked: what are the perceptions of change in understanding, following the experiences of a two-year GCSE Design and Technology: Electronics course? And what are the influences on such change? The approach adopted a mixed methods cross comparative methodology drawing from participant perception and self-report. The approach drew from Johnson and Onwuegbuzie's (2004) mixed methods design model with qualitative strategies the dominant status within a concurrent design. Three phases offered the opportunity to expose understanding at different positions in the learner's developmental trajectory and therefore the opportunity to make comparisons between understandings at those different points.

This approach was chosen because it offered an opportunity to gauge students' descriptive understandings and perceptions within context, whilst capturing a quantitative overview of perceptions through Likert-scale responses. Change in conceptual understanding therefore formed the unit of analysis for wider considerations of learning within an applied skills context. The research was bounded within the two academic-year time period of a GCSE course and therefore involved Ket Stage 4 students (age 14-16) undertaking the course. The case aimed to both exemplify understanding about the phenomenon (Thomas, 2011) and provide potential insight and extendability beyond the research setting (Van Wynsberghe and Khan, 2007).

4. Methods

Participants comprised seventeen boys aged 14-16 attending a selective state school in the South East of England. An information statement explained the research and the questionnaires were administered on an opt-in basis and under the conditions of anonymity. De-personalisation of comments was also clearly explained.

In Phase 1 (September 2016) open ended questions were used to elicit responses about participants' conceptual electronics knowledge. The approach drew from Solsona, Izquierdo and de Jong's (2003) essay writing technique which was intended to offer the opportunity to explain understanding in as much detail as participants were able to offer. This occurred at the beginning of the GCSE course where participants were assumed to be drawing from their knowledge of KS3 (age 11-13) Science and KS3 Technology lessons. Participants were asked the following three questions: 1) What is electricity? 2) How do you know this? and 3) How would you describe an electronic product? In addition participants were asked to complete the following statement: 'If I could see electricity it would be …'. The questions were designed to provide a baseline understanding about students' knowledge and the statement (Q4) was designed to explore possible analogy and metaphor use by participants.

Phase 2 occurred at the end of Year 1 (July 2017). Six open ended questions were used to determine the extent to which participants' experiences of Year 10 impacted their conceptual understanding of electronics, as follows: 1) What were the most interesting aspects of the Y10 course? 2) Which topics taught the most during Y10? 3) Which activities provided the greatest learning opportunities during Y10? 4) How would you describe the nature of electricity? 5) What is your understanding of the term 'electronics'? 6) What specific metaphors describe the behaviour of electricity?

Phase 3 occurred at the end of the GCSE course (May 2018). Questions were designed to capture participants' perceptions of their conceptual electronics knowledge after two years spent engaging with learning about electronics topics. In addition to questions focusing on electronics, the opportunity was taken to explore participants' views on the influence of a whole-school initiative to promote and apply the following dispositions for learning: ownership, courage, resilience, innovation and motivation. This was intended to explore the extent to which participants' self-efficacy and self-referential thought in relation to the five dispositions may have impacted their conceptual understanding.

4. Findings and Discussion

Analysis of Likert-scale responses used frequency response analysis to determine the distribution of answers. These are presented in the tables that follow. Comments from open ended questions were explored using the constant comparison technique. This involved systematically reading comments from questions to elicit themes, then developing categories describing the interconnection between emergent ideas (Thomas, 2013).

Phase 1: First lesson questions

Table 1 shows the findings from the first lesson questionnaire which focused on open-ended questions. Findings are arranged using a prominent/less prominent scale to present the responses in a clear and visual manner and include percentage weighting. The percentages indicate that more than one category was offered by some participants.

Question 1 revealed an understanding about electricity based on scientific knowledge and energy (85%). Less prominent were references to electricity used within products, possibly reflecting participants' limited experience with design at this stage in their learning.

Question 2 revealed that this understanding was gained largely through Key Stage 3 science lessons. However, a reasonably significant number (35%) cited their own discovery methods such as watching television or YouTube channels as prominent sources of information, some of these as a secondary source after KS3 science. This reflects a notable level of independent learning.

Question 3 explored electronic products knowledge by linking the products with their use of electricity. However, a significant number (50%) referred to physical aspects of products and their functionality. A small number (1%) made reference to programming and one participant referred to products in terms of users' needs.

Question 4 was designed to elicit answers that might indicate a more personalised understanding. The most frequent responses referred to imagined physical movement (Table 1, Q4), and the nature of that movement (e.g., 'looks like lightening' and a 'blue flash'). A significant number (45%) also indicated the benefits to safety and fault finding of observed electrical activity. The remaining responses included enabling observations of circuit behaviour, metaphorical description, and support for learning due to observable phenomena.

Question/Prompt	Responses (n=20)
	← Prominent Less Prominent→
1. What is electricity?	Scientific theory (85%); Form of energy (25%); Reference to a product (15%); Misconception (5%)
2. How do you know this?	KS3 physics/science (80%); Own discovery (35%) (e.g., TV, YouTube, personal experience); Primary school (5%); Design & Technology lessons (5%)
3. How would you describe an electronic product?	Link made with electricity (75%); Link with physical aspects of products (50%); Link with programming (1%); Link with user needs (5%)
4. If I could see electricity it would be …	A physical movement (35%); Would look like-lightning, orange sparks, blue flash, white zig-zag (35%); Would enable safety, enable fault finding (45%); Enable observations of circuit behaviour (15%); Metaphorical description (10%); Would support learning (5%); Fictitious innovation (5%)

Table 1: Key themes from first lesson questions

Summary of Phase 1

The findings from Phase 1 are categorised by a strong theoretical conception of electricity gained largely from KS3 science lessons. Some independent approaches to concept formation are noted including personally framed understandings of conceptions using metaphors.

Phase 2: End of Year 10 questionnaire

In Phase 2 a six-question questionnaire was completed by participants at the end of Year 10 which explored both understanding and course-based experiences. As in Phase 1, the questionnaire was designed to allow open-ended responses to provide rich description and illumination of understanding. Tables 2 and 3 provide an overview of responses. In the following commentary, key observations are made which draw out features of participant understanding, and which are of interest to the Discussion section below.

Q1			Q2			Q3		
GCSE Topic-Interest	**n=18**	**%**	**GCSE Topic-learning**	**n=18**	**%**	**Activity**	**n=18**	**%**
Programming	12	67	Electronics Basics	9	50	Circuit Wizard (computer software)	16	89
Timing	8	44	Timing	9	50	Practical/making	14	78
Gates	7	39	Gates	4	22	Breadboard	11	61
Electronics Basics	5	28	Programming	4	22	Worksheet	6	33
Counters	3	17	Counters	3	17	Programming	5	28
Op Amps	0	0	Op Amps	1	6	Note making	4	22
						Design HW	1	6
						Theory HW	0	0
						Other	0	0

Table 2: Phase 2 question response overview Q1-3

Q4			Q5			Q6		
Nature of electricity	**n=18**	**%**	**Understanding of term 'electronics'**	**n=18**	**%**	**Specific Metaphor**	**n=18**	**%**
Flow of electrons	11	61	Products needing electricity to run	6	33	Racing cars	3	17
Flow of charge	4	22	Device needing electricity to function	2	10	Water out of tap	1	5
Form of energy	2	11	Using electronics to problem solve and improve everyday life	1	5	Water in a tube	1	5
Form of power	1	5	Use of electricity for components and products	1	5	Water in a pipe	1	5
			Subject related to small products needing electricity	1	5	Water in a hose	1	5
			Study of making circuits work with electricity	1	5	Water	1	5
			Hand held project	1	5	People walking/queuing	1	5
			Hand held device needing electricity	1	5	Flow of water	1	5
			Creation of electronic products	1	5	East/west Germany (movement of people)	1	5
			A subject	1	5	A stream	1	5
			Nil return	2	10	A river	1	5
						Nil return	5	28

Table 3: Phase 2 question response overview Q4-6

Question 1 "What were the most interesting aspects of the Y10 course?" reveals a strong interest (67%) in programmed electronics. Although this was the most recent topic covered, observations of student engagement concur with this response. It is interesting to compare this with Question 3 which indicates that participants view programming as a minor (28%) vehicle for learning, despite this perceived interest. It might be that the on-screen nature of programming activities, which have been shown to symbolise electronics concepts and understanding (Twissell, 2018), mask developments in learning about electronics concepts. The remaining topics are shown to provide varying levels of interest for participants. Responses to Question 2 "Which topics taught the most during Y10?" may also represent participants' level of topic interest. Here it is not surprising that the 'electronics basics' and 'timing' topics form significant responses since these areas represented substantial sections of the course material. Programming as a topic is a slight anomaly (22%) as in Question 1 the topic was identified by 67% of participants as significantly interesting. However, as noted above the on-screen nature of programming may no elicit clear links to learning for participants and further enquiry may provide more detail.

It is interesting to note the value placed on practical application (78%), including through the use of computer software (89%), in responses to Question 3 "Which activities provided the greatest learning opportunities during Y10?". Circuit Wizard (New Wave Concepts, 2012) provides an applied on-screen approach to processing electronics knowledge, as does making a circuit or prototyping using real components. The procedures of circuit construction are not dissimilar between the two methods, including learning about the concepts of component position, orientation and polarity. The finding marks an acknowledgement and growing awareness of the practical nature of concept formation.

Responses to Question 4 "How would you describe the nature of electricity?" reflect the 'scientific' nature of electronics understanding highlighted in Phase 1 (Table 3). The basic conceptualisation does not appear to have changed during Year 10. However the response may be a product of the question phrasing. Since learning is considered in Question 3 to closely follow the use of ICT and application of practical approaches, it might be reasonable to suggest that 'the nature of electricity' could be conceived in a wider array of possibilities such as the metaphors featured in Question 6. This is discussed further below.

Responses to Question 5 "What is your understanding of the term 'electronics'?" focused on electronics as product (72%) and electronics as process (16.5%). It is interesting to note the strong reference to products and application, as opposed to a theoretical focus grounded in science concepts in the previous question. This may reflect the nature of the course of study, which revolves around product development rather the science of electricity. It may also reflect participants' concept development, where understanding is gradually progressing towards electronics applications and uses beyond theoretical explanations at the end of the first year of study.

Question 6 "What specific metaphors describe the behaviour of electricity?" explored the use of electronics-specific metaphors because they are considered to represent changes in conceptual understanding. It is interesting to note the nature of the metaphors (or analogies), as only one (water in a pipe) was introduced as a component of the GCSE course and therefore learning from elsewhere is being applied. The finding shows a development in metaphor use when compared with the Phase 1 questionnaire administered 11 months earlier. Although analogy and metaphor demonstrate conceptual change and reinterpretation of phenomena, metaphors have a limited lifespan (hence evidence of further conceptual change) since their application is limited to specific contexts and stages in the learner's development (Pitcher, 2014). Knowledge in the 'real world', in other words, only 'fits' metaphorically at times specific to learners' development. This demonstrates that conceptual change and the reinterpretation of concepts are highly context dependent.

Summary of Phase 2

Phase 2 responses are categorised by a developing understanding of the application of theoretical knowledge and how this relates to topics of interest on the course. Underlying theoretical understanding is largely unchanged, however an appreciation of 'theory in action' is emerging at the end of the first year of study. Learning is considered successful when opportunities for modelling and simulation of concepts is provided and understanding is increasingly individual, as reflected in the identification of personal metaphor.

Phase 3: End of GCSE course questionnaire

In Questions 1 and 2 participants were asked to describe the nature of the product and system they developed to satisfy the coursework component of the GCSE Design and Technology: Electronic Products course. These provided a context for the analysis of, and comparison with, responses to Questions 3 to 10. Responses provided technical descriptions of the projects developed, for example the following is adapted to enhance clarity "[I made] A temperature sensor/monitor [using] a thermistor … 7-segment display [and] PICAXE [microcontroller]" (Participant 4).

Question 3, "Given your answer in Q1 and Q2, how do you think your knowledge has changed during the course?", revealed a strong awareness of the functional aspects of electronic products. The following themes in relation to change in understanding emerged from responses: design, function, manufacture and use. These are shown in Table 3 with example responses for each theme and the focus of interest italicised in each case. The range of themes indicates a growing understanding of the application of theory, or 'theory in action'.

Question 4 asked participants to "describe how your understanding about electronics developed during these [Y10 and 11] two years". The following range of themes emerged from responses: design, effort/difficulty, function, manufacture and use. Table 4 shows responses for each theme. As in Question 3, there is a growing awareness evident in responses, of the practicalities of applying theory during designing and manufacturing.

Theme	Example Response
Design	"I now know more about how different components work, how they *interact with each other*, as well as *how to use them"* (Participant 6) "More importantly, I realise that *case design* and manufacture is also a major part [of the understanding]" (Participant 13)
Function	"The coursework has allowed me to understand *how many components work"* (Participant 3) "… the *function or result* of combining multiple components to create a certain/*desired output*" (Participant 9)
Manufacture	"I now know more about ICs and more *about how to manufacture* an electronic product" (Participant 12) "My knowledge has changed through *learning about the different manufacturing processes*" (Participant 2)
Use	"Overall my scientific knowledge has not changed much, *my understanding of how one can use it has changed*" (Participant 1)

Table 3: Themes from Q3 with example responses

Theme	Example Response
Design	"The Y10 projects definitely helped me plan and *design* my project in Y11" (Participant 17) "I can *fully design* a circuit without having to follow a blueprint" (Participant 6)
Effort/difficulty	"The two years allowed me to fully realise the *complexity* of developing an electronic product, and the huge amount of *effort required* to construct a functional product" (Participant 14) "It is very *difficult to transition* from Circuit Wizard to bread boarding and then to PCB design" (Participant 7)
Function	"I learnt the different components there are and *how they work*. I was able to identify different components and *know how they work*" (Participant 3)
Manufacture	"I now know how basic electronic circuits and components can be used to *make useful* products …" (Participant 4)
Use	"I have learnt more about electricity, *materials and the manufacturing process*" (Participant 12)

Table 4: Themes from Q4 with example responses

Question 5 asked participants to indicate which of seven situations were most useful to learning during the two year course (Figure 1). Responses concur with Phase 2 findings, which suggested practical application of theory, modelling and simulation as useful approaches to concept change. Figure 1 shows that the use of Circuit Wizard software (New Wave Concepts, 2012) and prototyping boards to model and simulate concepts were regarded as most useful. "Going through concepts with the teacher on the board" was also valued (n=3, 16%). The third option 'modelling circuit concepts' was perhaps an ambiguous option and possibly overlooked in favour of option 1 and 2. The 'Designing' and 'Making/trialling' options were possibly encompassed within the options chosen.

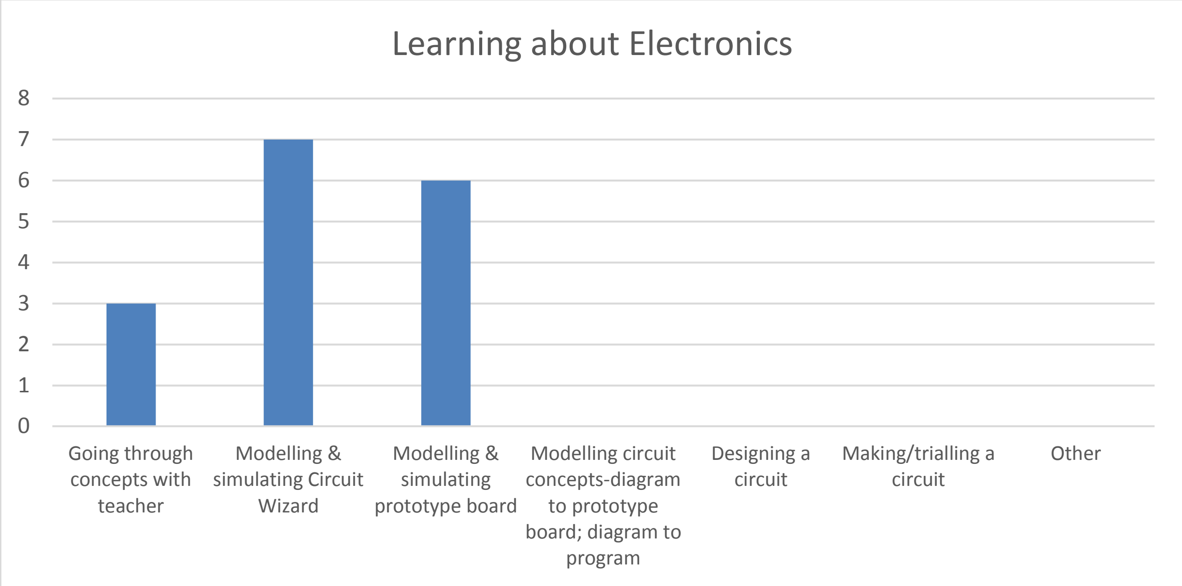

Figure 1: Question 5 responses based on Learning about Electronics

Responses to Question 6 ("Please explain your suggestion in Q5") expanded on the choices made in Question 5. The following themes emerged reflecting close links between modelling, simulating and developing understanding based on: experimentation, overcoming errors and practical action (Table 5).

Theme	**Example Response**
Experimentation	"It allowed me to see how different components would *perform under various conditions*, and to quickly and *easily alter the circuit*" (Participant 5) "Prototyping allowed me to *experiment with components* and identify how they work" (Participant 10)
Overcoming errors	"I *learnt so much from mistakes* made when building the circuit" (Participant 7) "[Prototyping] allowed me to identify and correct mistakes I made" (Participant 10)
Practical action	"I *learn by trying* and *improving* or *changing*" (Participant 1) "It was good to *physically see how components functioned in the real world* rather than with a program …" Participant 15)

Table 5: Themes from Question 6 with example responses

Question 7 asked participants to "rate the extent to which the following [institution-based learning] characteristics supported your understanding/knowledge of electronics". Overall participants viewed the learning characteristics as a positive support for learning about electronics (Figure 2). Particularly strong support for ownership, resilience, motivation and innovation may reflect the experience of the coursework exercise in Year 11, which necessitated a largely individual and independent attitude to learning.

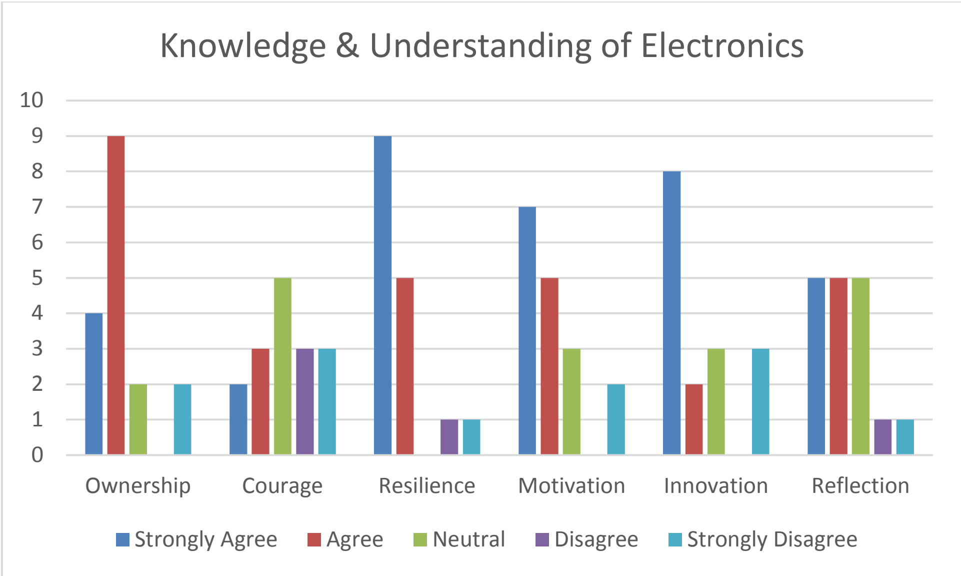

Figure 2: Dispositional perceptions of knowledge and understanding

Question 8 asked participants to "rate the extent to which the following (institution-based learning) characteristics supported the development of your coursework project". Figure 3 shows that, as in the previous question, there is strong recognition and support for the institution-based dispositions of ownership, resilience, motivation and innovation, which were considered to sustain project based learning (PBL).

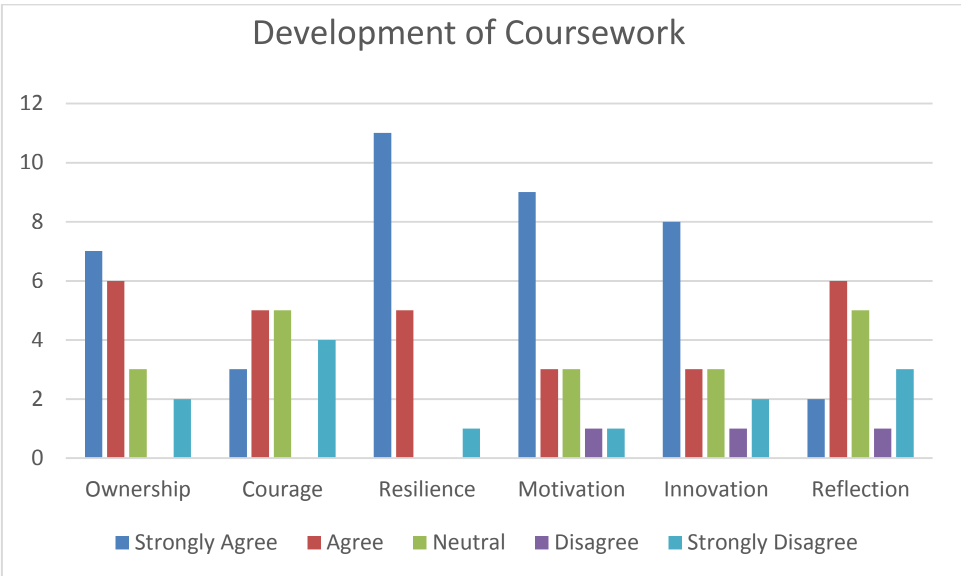

Figure 3: Dispositional perceptions of coursework development

Question 9 asked participants to "suggest any other learning dispositions that you found useful and explain how they were useful". Table 6 presents two responses ('determination' and 'making mistakes') linked with resilience, translation and research. Translation is an insightful observation which reflects a good understanding of the skills/strategies necessary to successfully convert representations in the form of circuit diagrams into working prototypes. The suggestion that research skills form a useful disposition for learning is also insightful, representing an understanding that learning necessitates assistance from knowledge bases outside of the learner's immediate awareness.

Disposition	**Example Response**
Determination	"Determination to *complete my coursework in time*" (Participant 12)
Making mistakes	"*Making mistakes*, meant that it was [perceived to be] impossible or these was 1 solution out of a billion methods of designing the circuit" (Participant 7)
Translation	"*Using* pinout diagrams from the internet … " (Participant 6)
Research	"*… researching how components work* using electronics websites" (Participant 6)

Table 6: Themes from Question 9 with example responses

Question 10 aimed to illuminate which one of three approaches to learning most closely matched participants' experiences of learning on the course. Figure 4 reflects some concurrence with Question 5, where responses supporting modelling and simulating activities might be considered to represent independent learning. However a significant number of participants (n=6, 35%) considered the social aspects of learning to be most beneficial (Figure 4) and this approach may have also included some independent activity which was subsequently discussed with others, but not apparent in the responses. Further exploration is needed to clarify this point.

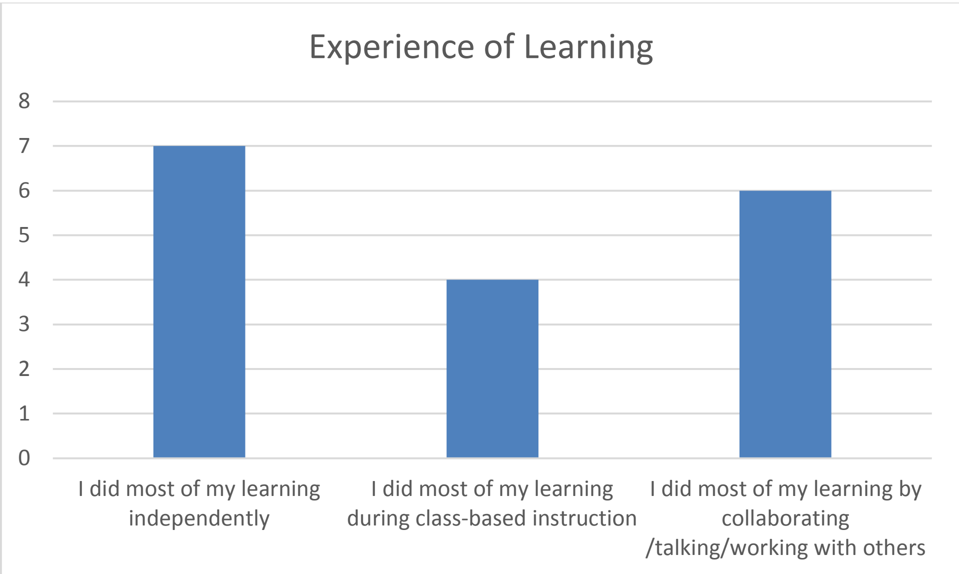

Figure 4: Personal perspectives on learning

Summary of Phase 3

Phase 3 findings are categorised by an increasingly pragmatic approach to conceptual understanding and knowledge development. Participants' responses reflect a strong focus on applying their knowledge, problem solving and goal achievement linked with the coursework phase of study. Descriptions of learning are grounded in the pragmatics of 'getting the job done' and personal descriptions of learning strategies, as reflected in awareness and support for institution-based learning dispositions and which follow the trend in learner agency and action identified earlier.

5. Discussion

This case study research aimed to reveal the nature of change in understanding about electronics concepts, as perceived by participants in the study, during a two year GCSE Design and Technology: Electronic Products course. In addition the study aimed to describe the influences on any change identified.

Comparisons between Phases indicate a step change in perceptions of electronics as a field of endeavour. Phase 1 findings reflect a theoretical view of electronics grounded in scientific knowledge gained mainly from previous study in Science lessons. The use of personal conceptions, for example metaphor, to describe understanding is beginning to appear at this stage. In Phase 2 understanding is shown to begin to adjust to the pragmatics of applying theory to the development of electronic product prototypes. The translation of knowledge, through modelling and simulating activities, reflects a procedural approach to understanding how electronics theories work in practice. Findings from this Phase are categorised by the strong functional nature of participants' growing electronics knowledge which is also individually characterised. This approach aligns with the demands of the course-based activities, which draw on the use and development of procedural knowledge; that is, understanding is a product of the knowledge gained through experience.

Phase 3 findings indicate that the process of carrying out individual project work may lead to a more personalised attitude to learning. The institution-based learning characteristics including ownership, resilience, innovation and motivation were perceived to positively support learning and to complement the development of understanding, particularly within a problem solving focused learning context.

Understanding was therefore shown to adjust to meet the demands of the context, supported by self-referential thought encouraged by the school's taxonomy of learner characteristics. Conceptual change is categorised by the modification of schema representing electronics knowledge. The change is reflected in an initial understanding grounded in science-based theory, reinterpreted to represent the application of theory during designing, modelling and making activities. The process of change is underpinned by the application of translation strategies, for example modelling and simulating electronic circuit schematics using virtual computer software-based techniques and the associated reflection on change and revision of conceptual schema.

However, the finding during Phase 3, indicating that 35% of participants regarded collaborative working as an important factor in their learning (Figure 4), shows that working beyond the personally-based dispositions is also a key support for learning. Both Costa and Kallik's (2002) and Lucas et al.'s (2014) habits of mind models include dimensions incorporating listening, understanding, empathy and collaboration. These dimensions would form useful avenues for further research exploring conceptual change in specific contexts, such as applied skills learning.

Overall, within a modified conceptual change theory of learning, these findings support the analysis by Kural and Kocakulah (2016), who assert that cognitive, metacognitive, personal disposition such as motivation and self-efficacy factors contribute to conceptual change. The findings indicate that a combination of active engagement in the process of attending to conflicting conceptual ideas, coupled with a self-awareness of the methods used to develop those ideas, supports advancements in complex abstract concept understandings. The following section outlines a model of change based on the preceding discussion and which incorporates a number of practical strategies to support conceptual change and how this might be encouraged and developed within a model of sustainable independent learning.

5. Toward a Model of Sustainable Learning

Drawing from a combination of Bruner (1977), Kolb (1984) and Piaget's (1955) constructivist theories, this section outlines a structured approach to developing sustainable learning strategies to encourage conceptual change. I refer to this model as the *Four 'R's Model of Sustainable Learning* (Figure 5). The four 'R's refer to the following strategies: relate, reinterpret, reflect and revise which are considered to support learners' schema development and are here incorporated with Piaget's (1955) assimilation/ accommodation processes (Figure 5). The strategies are 'sustainable', because they have the potential to develop understanding beyond the resources offered by formal education. Learning thus becomes more independent and places an emphasis on the development of curiosity and autonomy as central learning skills when the four 'R's are successfully applied.

Previous research by Twissell (2018) revealed the importance of reinterpretation as a central strategy to increase learners' depth of learning. The personalisation of knowledge was shown to be an important attribute of the learner's strategy when reinterpreting, problem solving and developing conceptual schema. The Four 'R's Model of Sustainable Learning is proposed as a framework for operationalising a personal learning process which can be developed and applied in multiple contexts and sustained beyond formal educational objectives.

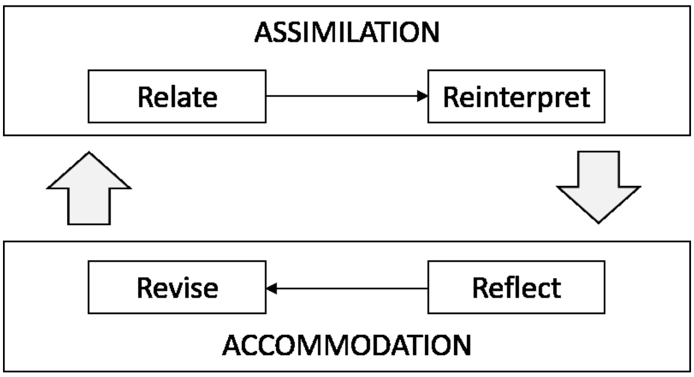

Figure 5: Four 'R's model incorporated into
Piaget's process of assimilation and accommodation

Figure 6 provides an overview of the four 'R's framework and each element is now discussed in more detail.

A. Relate

Piaget's (1955) theory of schema modification describes how learners bring new knowledge into existing understandings. They relate, or assimilate, new knowledge with existing understandings. Research with secondary age learners of electronics (Twissell, 2018) showed that this was the most frequently chosen strategy when learning about complex abstract concepts. Learners in this study were shown to relate their existing theoretical understanding of electronics to their own observations of functioning models and simulations. Developing learners' awareness of this link between knowledge types and use of the knowledge relationships is a useful starting point for developing a metacognitive approach and route to reinterpreting understanding through translation, modelling and simulation.

B. Reinterpret

Bruner's (1977) learning taxonomy emphasises the need for the manipulation of knowledge once it has been brought into existing understanding. Reinterpreting in this way provides the learner with the opportunity to appraise the new knowledge within a new situation, therefore learners' breadth of understanding is widened to meet the demands of the new situation. The reinterpretation of conceptual knowledge is often achieved through modelling and the simulation of concepts (Figure 6). This may involve, for example, converting knowledge from one representation type (circuit diagram) to an alternative type (physical model), thus providing the opportunity to view phenomena in alternative ways.

C. Reflect

According to Bruner (1977), once knowledge has been reinterpreted or 'manipulated', the learner checks its plausibility. Kolb's (1984) experiential learning cycle, similarly, includes a reflection on experience phase where questions can be directed to clarify understanding. For example is the outcome plausible? Does it work? Does the new knowledge 'fit' within the context? Reflecting provides an opportunity to attend to the change, development and improvement of knowledge and understanding in light of the new learning experience. Participants 5 and 10 provide a relevant example with respect to experimentation and overcoming errors (Table 5) where reflection would have been central to the recognition of knowledge development.

D. Revise

Revising schema involves changing existing understanding to accommodate new knowledge. Reinterpretation is itself a process of revision in the short term, but revision of schema involves a greater shift in understanding. As discussed above, Piaget's (1955) notion of assimilation and accommodation has been described in terms of the process of conceptual change (Chen et al., 2013; Ozdemir and Clark, 2007; Treagust and Duit, 2008). This describes the process of reinterpretation and revision of schema formed in previous and alternative ways and has focused on both the cognitive and affective domains to explain an individual's learning engagement when refining understanding. Knowledge in this way is developmental, fluid and personal, rather than rigid and fixed, as demonstrated by the findings in this case study research. According to Knapper (2006), this process of change is characteristic of contemporary ways of thinking about learners, their development and learning. Revision of understanding is therefore central to the process of conceptual change.

Sustainable Learning: A Four 'R's Framework for Cognitive Skills

RELATE	▪ Relate phenomenon to existing knowledge ▪ Arouse existing understandings ▪ Make comparisons ▪ Connect knowledge ▪ Seek patterns/similarities
Model ▪ In real world/practical approach ▪ Using symbol systems *Simulate* ▪ Trialling & interpretation of modelling	**REINTERPRET**
REFLECT	▪ On new knowledge/simulation/ interpretation ▪ Is it plausible? ▪ Does it 'fit'? ▪ How does it compare with original understanding? ▪ What are the collective /opposing/confirmative views from discussion with others?
▪ New knowledge acquisition replaces/modifies existing understanding	**REVISE**

Figure 6: Four 'R's for sustainable learning framework

6. Limitations of this case study research

This research study adopts an assumption that learning is gradual and linear. However although the findings reflect a reasonably consistent progression, from a theoretical understanding to a pragmatic approach which reflects the practicalities of problem solving, it is known that learning is often both highly variable among learners, and across periods of time (Siegler, 2005). While this research adopted a phased approach to capturing perceptions of learning, introducing 'microgenetic' observations (*ibid,* 771) of learning may further increase understanding about learners' variable approaches and how these materialise across different timeframes.

7. Conclusion

This case study research aimed to explore changes in conceptual understanding as perceived by participants following a General Certificate of Secondary Education (GCSE) Design and Technology: Electronic Products course. The study developed Twissell's (2018) previous research, which identified a taxonomy of conceptual profiles, by exploring how learners' conceptual understandings change and evolve in the development of such profiles. The study explored learning through the lens of conceptual change theory, which describes a particular view of learning based around the gradual modification of knowledge schema.

At a theoretical level, this research contributes a learner perspective on conceptual change which draws from the constructivist theories of Bruner (1977), Kolb (1984) and Piaget (1955). The findings suggest that through the experiences of modelling and simulating abstract conceptual phenomena, understanding gradually changes and learners' attitudes to learning adopt a more pragmatic stance which is focused on the practicalities of applying theoretical ideas to problem solving rather than on the principles of theoretical knowledge as 'object'. In addition, learners' personal learning character, or disposition for specific approaches was shown to be an important feature in support of the strategies used to solve problems; particularly within a project-based learning phase of the course. Their ownership, resilience, motivation and innovation were found to support the development of both knowledge and understanding and practical coursework-based tasks. This finding supports Kural and Kocakulah's (2016) assertion that conceptual change involves a multidimensional array of factors including cognitive, metacognitive and specific dispositions for learning to achieve a modification in conceptual understanding.

The findings also indicate that collaboration was a key dispositional dimension in learners' approaches to learning. Further research to identify how collaboration informs and supports learners' development of personal schema would enable a more informed approach to the design of learning instruction and engagement.

At a practical level, this research contributes a *Four 'R's Model of Sustainable Learning* which describes a practical approach to developing cognitive skills which may lead to the development of abstract conceptual understanding. The model builds upon

Piaget's (1955) assimilation/accommodation process, providing specific strategies for achieving conceptual change based on the four principles: relate, reinterpret, reflect and revise. The model has the potential to apply beyond the applied skills subjects discussed in this case study research.

About the Author

Dr. Adrian Twissell is a technology educator specialising in engineering, electronics and micro-control. His research interests include teaching and learning pedagogies that utilise visualisation strategies and their application in the development of conceptual understanding. Dr. Twissell gained his Doctorate in Education from Oxford Brookes University, Oxford, UK. His doctoral research explored the use of, and interplay between, multiple representations as strategies for learning about electronics within the context of applied skills learning and embodied cognition.

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