THE UNIVERSITY OF HULL

Approaches Used by Science Disciplines When Solving Open-ended Problems and Their Links to Cognitive Factors

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by

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Abstract

Solving problems is a key skill required for developing academic success and is desirable to graduate employers across a wide variety of industries and, as such, needs to be valued by both educators and learners. This thesis describes the investigation into what approaches are used by different science disciplines when solving open-ended problems and how these relate to an individuals ability to process information (M-capacity) and their ability to dis-embed information (field independence).

Qualitative data was collected through think aloud sessions with first year undergraduate students in six science disciplines in order to identify the approaches they used. Further data was collected from chemistry academics, industrialists and postgraduate students and academic groups. The qualitative data was analysed using a grounded theory approach.

Quantitative data were collected from science participants in six disciplines to investigate relationships between approaches used and M-capacity and field independence. Data was collected using the Figural Intersection Test (FIT) and the Group Embedded Figures Test (GEFT).

The results showed that there were eight discrete approaches used when solving open-ended problems. A hierarchy of success at solving open-ended problems emerged from different science disciplines through two separate foci. The first is that physical sciences students have the greatest success at solving open-ended problems and psychology participants having the least success. The second foci is that chemistry academic staff have more success than industrialist participants who in turn have more success than

undergraduate students. These hierarchies have been attributed to the amount of evaluation used and the effective use of mathematics.

The quantitative data identified correlations between M-capacity and success at solving open-ended problems, and between field independence and approaches used.

The implications of the findings are discussed and recommendations for further work are identified.

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1 Introduction

This chapter focuses on a literature review of three components within this project. The first topic will be a review of the fundamentals in the development of cognition and learning, directing focus towards working memory and attention. The review will then discuss the current research related to problem solving within science, specifically problem solving research in chemistry and studies involving comparisons between experts and novices. Finally the chapter will present an analysis of the different philosophical worldviews and frameworks used in qualitative chemistry education research.

1.1 Cognition and Understanding

Cognition is the mental act or process by which knowledge is acquired and includes perception, intuition and reasoning[1] covering areas of development in thinking, language and memory.[2] Knowledge is provided by a stimulus from the environment and is processed through a variety of cognitive processes to achieve understanding.[3] These stimuli are very important in understanding the epistemic nature of learning behaviour and have been employed in many disciplines such as psychology, linguistics and education.[3] The early studies of cognitive behaviour centred on understanding the cognitive processes and developing a model of understanding. The initial model developed was the Serial Processing[3] model where a linear progression, using individual cognitive processes, is employed (Figure 1).

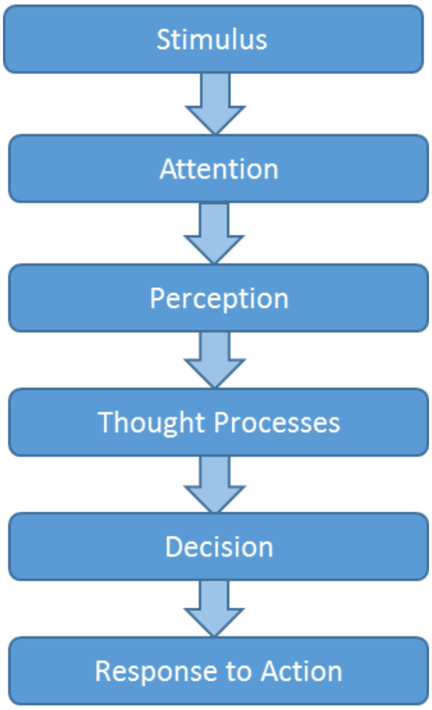

Figure 1 The early version of the serial processing model.[3]

With this model the individual is exposed to a stimulus, whereupon the brain works through the cognitive processes such as attention and thought processes etc. The individual starts from a situation of no knowledge and, using cognitive skills, deduces understanding to reach an outcome (knowledge) or reaction (response). This learning model received criticism, being rejected as being overly simplified and ignoring the prior knowledge already obtained by the individual. This led to the addition of the top-down processing model. The top-down model works by using the individual's prior knowledge and expectations rather than starting with the stimulus. As a result the individual is allowed to make assumptions or inferences, 'going beyond the information given'.[4]

As a result of various research studies most cognitive researchers believe that humans need a combination of both the serial processing and the top-down approach when exploring the world around them. A key example of this is Bruner, Postman and Rodrigues who experimented with the perception of colour.[5] In this study participants were shown a set of playing cards where the hearts were black. Some of the individuals reported seeing purple or brown hearts, meaning there was a blending of the serial processing (the heart I am seeing is black) and the top-down approach (I know that hearts are red).

As a result of ongoing development in cognitive models, a new model was developed and adopted called the parallel processing or cascade processing model. With this model, all or some of the processes involved in completing the cognitive task are experienced at the same time. This is a model that is suitably applied to those highly skilled and practiced in performing the task.[3] For example, a student learning to fly may struggle to remember to use the rudder pedals and the joystick correctly whilst talking to the control tower, whereas an airline captain should be able to multi-task with these roles.

At around the same time as the philosophical processing models were being created and assessed, three founding theories of experimental cognitive psychology emerged; Piaget (Stages of Cognitive Development), Vygotsky (Social Development Theory) and Bruner (Scaffolding Theory)[3] Although these theories were developed using children as the participants, it should be noted that the stages of cognitive development (such as formal operational and abstract thought), social development theory (learning through social interaction) and scaffolding theory (learning from ‘experts’ and symbolic representation) all have direct impacts on models of learning and understanding in higher education, and in particular, science education. The theories of learning and development are the foundation stones of cognitive concepts such as working memory, attention and the information processing model, allowing educators to understand how their students learn.

1.1.1 Piaget's Stages of Cognitive Development Theory

Piaget believed that there was a genetic epistemology, that is, we can understand the world by learning how understanding develops in children.[2] His focus was the role of development in a person's ability to understand their environment. He proposed that the individual's intelligence was irrelevant in performing certain tasks, which could not be done until they were psychologically ready (developing maturity).[6]

Another concept developed by Piaget was that "logic is the mirror of thought,"(pg30)[7] meaning that human reasoning can be expressed in a similar manner to the way logic is expressed by pure mathematicians. This is not to say that they were the same, as the terms quasi-logic and psycho-logics were coined to express their difference. However, this theory has been rejected in its entirety by most psychologists who believe that human reasoning is based more around an individual's ability to adapt to their environment, although aspects of the theory still hold some validity. Piaget's theory identified four stages of cognitive development (Table 1), which explained how, when a child reached a certain level of maturity, they were able to perform particular tasks and learn in a certain way.

Table 1 Piaget's stages of cognitive development

Cognitive Stage of Development	Key Features	What does it mean?	Research Study
Sensorimotor 0-2 yrs	Object permanence	At this stage the learner understands that an object continues to exist even when they cannot be observed.	Blanket and Ball Study[8, 9]
Preoperational 2-7 yrs	Egocentrism	The learner believes that other people see, hear, and feel exactly the same as they do.	Three Mountains[10]
Concrete Operational 7-11 yrs	Conservation	The learner understands that something stays the same in quantity despite a change in appearance.	Conservation of Number, Volume[11-13]
Formal Operational 11 yrs+	Manipulate ideas in head as abstract reasoning	The learner is able to manipulate ideas in their head without requiring concrete manipulation	Pendulum Task[14]

Although Piaget's theory of stages of cognitive development was developed using children, and although some psychologists dispute the age categorisations that Piaget affixes to each stage, what is indisputable is that these stages exist. Furthermore, it has been demonstrated that some individuals will never acquire the necessary thought processes associated with the cognitive stage of formal operational.

1.1.2 Vygotsky's Social Constructivist Theory

Vygotsky was born and raised in communist Russia where his developmental theories were influenced by the Marxist ideology, emphasising the role that social interaction, culture and play had in developing knowledge, and the interaction between cognitive development and learning. He believed that cognitive development could not occur in a 'social vacuum.' He viewed development as our ability to think and reason with ourselves and others as a result of social exposure from birth, where we interact with our environment but are practically or intellectually incapable of doing so without the support of others. Gradually, as we get older we transfer to greater self-sufficiency transforming our capabilities through social interaction, and in particular through dialogue. In order for this transformation to occur a process of active internalisation of problem solving must be present and influenced through a social hierarchy such as friends and relations, this was later to be called Social Constructivism. In contrast to Piaget, Vygotsky believed that the child is the apprentice in the knowledge development relationship rather than the 'child scientist,'[15] acquiring their knowledge through culture and graded collaboration with those already possessing the desired knowledge.[15] Vygotsky stated that "Any function in the child's cultural development appears twice, or on two planes. First it appears on the social plane and then on the psychological plane."(pg 163)[16] He believed that there were two levels of function; elementary mental functions and higher mental functions. Elementary mental functions are those that are present from birth and only show minor development through experience. Higher mental functions are those that are required by problem solving, mathematical ability and language. Vygotsky believed that cultural influence was required for a transition from the elementary to the higher mental functions. Since higher mental functions are influenced through culture, then different cultures should be able to develop different higher mental functions.[17] Once a child has developed these 'tools'[18] they 'internalise' those skills and become part of the child's arsenal of tools for learning. Language is the biggest tool that Vygotsky relies on for his theory, wherein he explains that there are two stages of language; the inner voice (internal thought) and the communicative voice (speaking aloud). This inner speech is vital in problem solving. However, in the early stages of development the inner voice is vocalised as private speech, in an attempt at self-guiding and focusing attention on the task required. Children aged 6 spend 60% of their time talking to themselves whilst solving mathematical problems, and as a result retain the skill of mathematical problem solving.[19] As a child becomes more confident with their understanding private speech becomes more internal. Thus Vygotsky assumed that private speech is of most value when confronted with novel tasks. However, an issue arises when examining deaf individuals, who experience novel tasks but do not participate in private talk as it holds no function, yet still do not suffer from impaired intelligence as a result.[3]

A further theory developed by Vygotsky is the zone of proximal development (ZPD) where “what is the zone of proximal development today will be the actual zone of development tomorrow. That is, what a child can do with some assistance today they will be able to do by themselves tomorrow,”[18] and through this bridge the gap between ignorance and knowledge. The zone of proximal development is referred to as the model that “defines functions that have not matured yet... called the buds of development.”[18] The model has been adapted since Vygotsky’s first proposition and incorporates the following stages

1. Stage 1: Assistance from “more knowledgeable other” (capable peer or adult).
2. Stage 2: Assistance from self (prior knowledge and research)
3. Stage 3: Automatisation (practice, trial and error)
4. Stage 4: De-automisation (provide explanation to others)

A characteristic observed by Moss in 1992[20] and Conner *et. al.*[21] was that parents provide structure for their children in three particular ways:

1) A mother instructs the child with knowledge and strategies they would not otherwise know.
2) A mother encourages a child to use these new strategies.
3) A mother discourages inappropriate behaviours.

A further study by Freund[22] involved assessing the importance of structure and ZPD of children placing furniture into rooms in a house. Freund concluded that ZPD led to greater understanding and performance than working alone.[22] Mothers of gifted and talented students structured their tasks with more emphasis on metacognitive strategies,[23] and those from a higher social standing were more likely to stimulate their child's zone of proximal development than those of a lower social standing.[24] This may suggest the emphasis certain social groups place on education and learning, a concept that may follow through until higher education.

There are some criticisms of Vygotsky's social developmental theory. Primarily, the motivation of the child is not considered in the development of their knowledge and failure and frustration with a task may inhibit their ability to acquire knowledge, rather than it being based solely on environmental impact.[25] Furthermore, Vygotsky never defines which social interactions are best for encouraging learning and some can be counterproductive. For example, too much criticism can make a child more determined to do things their own way, whether it's wrong or right.[26] The lack of maturity stages falls into direct conflict with Piagetian philosophy as, despite plenty of social support, some individuals are incapable of grasping certain concepts, and as such Vygotskian social development theory must involve other developmental factors and can't really stand alone as a theory.

1.1.3 Bruner's Constructivist Theory

Bruner developed his initial work at a time when cognitive development was dominated by the behaviourists. Bruner believed that learning was an active process with learners developing their own knowledge supported by their prior knowledge. According to Bruner, a child's cognitive function matures with age and he or she is increasingly able to think and organise material of greater complexity. His initial comments are similar to Piaget's model of cognitive development. Bruner recognised that children have a natural curiosity and yearn for knowledge and understanding resulting in natural adaptation to their environment.[27] This results in abstract thought occurring through action, rather than solely mental maturity. Bruner believed that children learn best when they have to learn for themselves and try and make sense of the stimulus and environment they are exposed to. He also believed that the observed world and our perception is a result of our own mind, a concept of an 'extreme constructivist'.[28] There is a lack of stages of development in this theory as Bruner believed greater importance should be placed on the representation and organisation of knowledge in the child as they develop. Bruner did, however, postulate the modes of representation. These differ from Piagian stages in that once a child progresses, they don't forget the skills developed in the previous mode. There are three key areas identified by Bruner (Table 2):

Table 2 Modes of representation, the ages experience and the characteristics exhibited

Modes of Representation		
Mode	**Age First Observed**	**Characteristics**
Enactive	1st year	Thinking is a physical action, physical manipulation
Iconic	2nd year	Mental images, lacks ability to solve problems. Draws on experience to express one's self.
Symbolic	6-7 years +	Recognition of words, music and numbers, increased linguistic skills

1) Enactive: This stage of development is very similar to Piaget's initial stages of sensori-motor, whereby the child explores their new world through physical interaction rather than visual interaction. It is first exhibited during the first year of a child's life, and is perceived as the least complex form. The child's mental faculties are rudimentary, resulting in thinking as a physical action. Tasks that fall into this envelope include tying knots, or holding a teddy. Later in life these mental faculties will develop into learning to swim or driving a vehicle. These stages are enactive, because it proves problematic when trying to explain to another how to tie their laces or ride a bike.

2) Iconic: This mode is similar to Piaget's transitional stage between sensorimotor and pre-operational stages of development and in general first manifests in the second year of life. In this mode the child is able to formulate mental images, allowing them to still visualise the object even after the stimulus is gone. It is also a mode where you are able to draw on all previous visual stimuli to create an idealised mental image of an object. For example, there are many different forms and shapes of a car, but

through experiences, the mental image created is based on these multiple exposures resulting in the idealised mental image of the car.

3) Symbolic: This mode is similar to Piaget's Concrete Operational stage of development and develops between 6 and 7 years. Bruner categorises symbolic to mean words, music and numbers, anything that can used to symbolise an object, without either the object or the mental image. The precise stage that this develops depends on the linguistic skill of the child, and allows the child to categorise objects, apply logical thought and solve problems.

Bruner's main concern was the transitional period between iconic and symbolic modes, and whether an individual could increase the speed of their symbolic recognition through training in which language plays a major role.[29] However, this is not essential as deaf students are still able to develop abstract thought.[30] This contradicts Piaget's theory that suggests each stage is predetermined through developmental stages fixed by the age of the student.[31, 32] Bruner postulates that we possess a language acquisition social system (LASS), where the child develops language based on exposure to facial expressions and mannerisms and, therefore, must be learnt in a social context.

Furthermore, Bruner is the founding theorist of scaffolding theory. Wood *et*. *al*. state that the tutoring process at solving problems is when "an adult or 'expert' helps somebody who is less adult or less expert."(pg 89)[33] Bruner believed that four principles must be addressed in order for students to learn:

- Firstly students must be willing and engaged with the experiences and context of which they are learning. There must be a predisposition for the student to learn in order to maximise the cognitive processes to construct understanding.[34]

- Secondly learning tasks and instructions must be designed so that the student can easily comprehend the scaffold provided. If the student is unable to comprehend the scaffold then the instructions provided by the tutor are worthless to the learning process.[34]
- Thirdly, in order for students to construct their understanding they must be able to think beyond the information that they are provided, so that they themselves can fill in the gaps of their understanding supported by the scaffold.[34]
- And finally, good scaffolding should result in students being able to manipulate information, simplification and construct new ideas. This ensures that the student can develop a true understanding and reasoning skills ready for learning future concepts.[34]

Wood *et. al.* further stated that through Bruner's theory the "scaffolding process enabled a child or novice to solve a problem, carry out a task or achieve a goal which would be beyond his unassisted efforts. This scaffolding consists essentially of the adult 'controlling' those elements of the task that are initially beyond the learners capacity, thus permitting him to concentrate upon and complete only those elements that are within his range of competence."(pg 90)[33] This means that the teacher/tutor provides the scaffold to the activity and provides support at the appropriate time. Under Bruner's theory the teaching mechanisms employed by the teacher/tutor supported the individual student who then constructs their own knowledge and understanding, rather than depending on the interpretations of the society to which they belong. This slightly differs from the Vygotskyian approach for providing structure with the zone of proximal development, who fell short of stating that the student never develops knowledge independently. Vygotskian theory believes that problems arise in the learning process when too much information is left to the student to understand independently, with students learning best through assisted social learning and guided participation.[18] Through Vygotskyian theory the student is mimicking the social interactions of the society rather than through the construct of their own understanding.

1.1.4 Working Memory

Working memory is a model proposed by Baddeley and Hitch in 1974[35] and is a "limited capacity system that is capable of storing and manipulating information and is assumed to be an integral part of the human memory system,"(pg 13468)[36] yet it is not a "unitary system", it has functional roles in other cognitive tasks such as learning reasoning and comprehension.[36] Working memory was perceived by Baddeley as a four-part system, with two slave functions (phonological loop and the visuo-spatial sketch pad) holding and recording information controlled by an executive that controls attention.[37] The fourth component is the episodic buffer which provides a temporary storage system that integrates the phonological loop and the visuo-spatial sketchpad[3] (Figure 2).

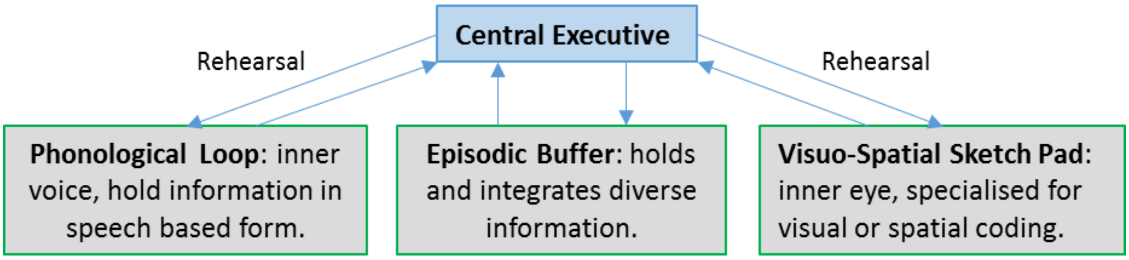

Figure 2 Major components of Baddeley's working memory system[3]

These four functional systems of working memory allow for switching between active long term memory and information processing. The phonological loop is responsible for holding and processing acoustic and speech based information and is closely associated with language acquisition. The visuo-spatial sketch pad is less understood, but is believed to be similar in operation to the phonological loop but deals with visual stimuli. What makes studying the sketch pad complex is that some of the functions rely heavily on the central executive which is understood even less. It is believed that the central executive has a limited storage capacity and functions similar to attention in that it focal point for stimuli, being responsible for processing both auditory and visual stimuli requiring high cognitive demand.[3] That is to say, the central executive emerges when a task requires a high cognitive demand beyond basic memory storage. Investigating the relationships between these multiple functions of working memory is completed using interference tests where one function is separated from the others. If there is no interference between working memory functional systems recorded then the systems are assumed to be independent.[38] All three of the processing functions (phonological loop, episodic buffer and visuo-spatial sketchpad) function relatively independently from each other under two assumptions:

1) If two tasks require the same function they cannot be performed successfully together
2) If two tasks require different functions then the two functions should perform just as well at the same time as they would working independently.

A study by Robbins *et. al.*[39] sought to assess the involvement of the three functions in the selection of moves performed by expert and novice chess players. The individuals had to move chess pieces whilst performing a selection of different tasks. The study demonstrated that moving a chess piece required the central executive and visuo-spatial sketchpad but didn’t require the phonological loop. As such the individual would be able to perform additional tasks that required the phonological loop but not those requiring the visuo-spatial sketchpad.[39] Table 3 summarises what each of the sub-functions in working memory are believed to be responsible for and the evidence for their existence.

Table 3 Description of different functions in working memory and the evidence for their existence under the Baddeley and Hitch Working Memory Model

Function Name	**Description**	**Evidence**
Phonological Loop	A function of working memory with a limited brief store capacity for auditory and written stimuli. It comprises of two components; the phonological store and the articulatory control process. It is considered a slave system.	Phonological similarity effect.[40] Word Length Effect.[3, 41, 42] Linguistic Effect of Learning New and Foreign Words.[43, 44]
Visuo-Spatial Sketchpad (VSSP)	A limited brief store capacity for processing information from visual and spatial stimuli. It comprises of two components; the inner scribe and the visual cache. It is considered a slave system	Visual Impairment due to auditory stimuli.[41, 45] Spatial performance linked more to visual recall rather than visual store.[3] Comprises of two sub-sections: visual cache and inner scribe.[46] Processing visual stimuli is not done solely by the VSSP, and requires both visual and spatial processing.[47]
Central Executive	A limited storage and control system which is responsible for monitoring and coordinating the two slave functions. It is also thought to be the conduit between working memory and long term memory. Difficult to isolate specific tasks solely completed by the central executive.	The central executive is thought to be responsible for: • Switching attention between tasks.[48-50] • Planning sub-tasks to achieve some goal.[50-52] • Selective attention and inhibition.[48-50] • Updating and checking the contents of working memory.[50] • Coding representations in working memory for time and place of appearance.[50] • Temporary activation of long term memory.[48]
Episodic Buffer	Functions as limited capacity storage system responsible for integrating stored stimuli in phonological loop and VSSP stores into one episode. Considered a slave function in working memory.	Memory span test for Arabic numerals and digit words.[53] Immediate memory span test in phonologically brain damaged patients.[54]

1.1.5 Attention

Attention refers to the selectivity of brain processing. As James[55] describes it "everyone knows what attention is. It is the taking possession of the mind, in clear and vivid form, of one out of what seem several simultaneously possible objects or trains of thought. Focalisation, concentration, of consciousness are of its essence."(pg 403)[56] James believed that attention consisted of two modes, active and passive. Active attention is when thought is controlled through an individual's goals and expectations. Passive attention is when thought is stimulated through external stimuli.[57] There is also the differentiation between two key areas of attention research which are focused attention and divided attention (Figure 3).

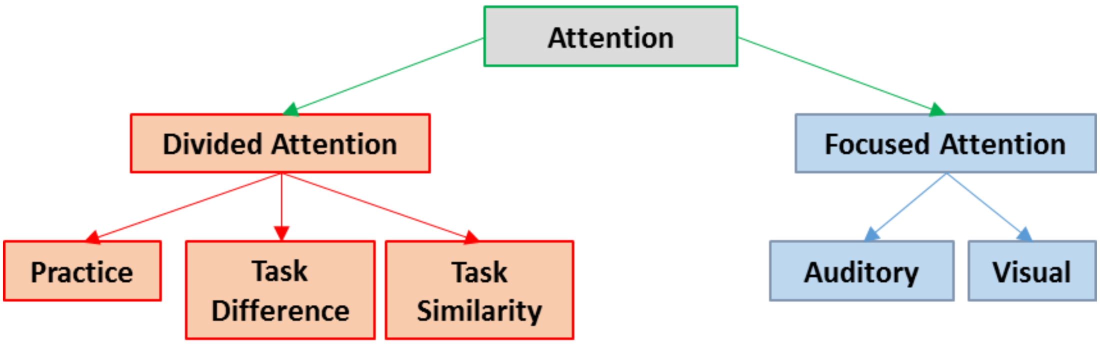

Figure 3 The ways in which different topics in attention are related to each other.[3]

Focused attention is studied by presenting two or more stimuli at the same time and instructing participants to only respond to one.[3] This tells researchers how people make decisions, the nature of the selection process and the effects towards the unattended stimulus. However, a response has to be made to all stimuli; this provides scientists with information about an individual's processing limitations and attentional mechanisms. There are significant limitations with attentional research. Firstly, the research is incapable of testing both external environmental stimuli and internal environmental stimuli (internal thoughts and long term memory). Most research has been conducted using external factors of attention because it is easier to influence than internal factors. Secondly, the response to a stimuli can be determined through current goals and objectives as there are no bridge between attention and motivation meaning they are interdependent.[58] Most research however, would suggest that individuals respond more to the experimenter's instructions rather than motivation.[3] Finally, the real world functions in '3 dimensions' and as such participants respond suitably with respect to their actions. However, a majority of lab situations are "static 2D displays and requires arbitrary responses... [these] are rarely encountered in our usual interactions with the environment."(pg 902)[59]

1.1.6 Information Processing Model in Science Education

The multi-store model developed by Atkinson and Shiffin[60] developed the initial model used by many science educators describing the role of memory in learning. Their model described the process of memory processing in the terms similar to a computer, with an input, process and output components. In Figure 4 the information is initially detected by the sensory register through the sensory organs. If the information is attended to then the information enters the short-term memory. Information from the short-term memory is then transferred to long-term memory, but only if the information is rehearsed (maintenance rehearsal).[60] However as previously discussed the initial thought that short-term memory was a unitary system was massively over simplified. Furthermore the model proposed by Atkinson and Shiffrin has been criticised for being too linear, and not accounting for memory recall of information which isn't rehearsed (riding a bike, swimming).

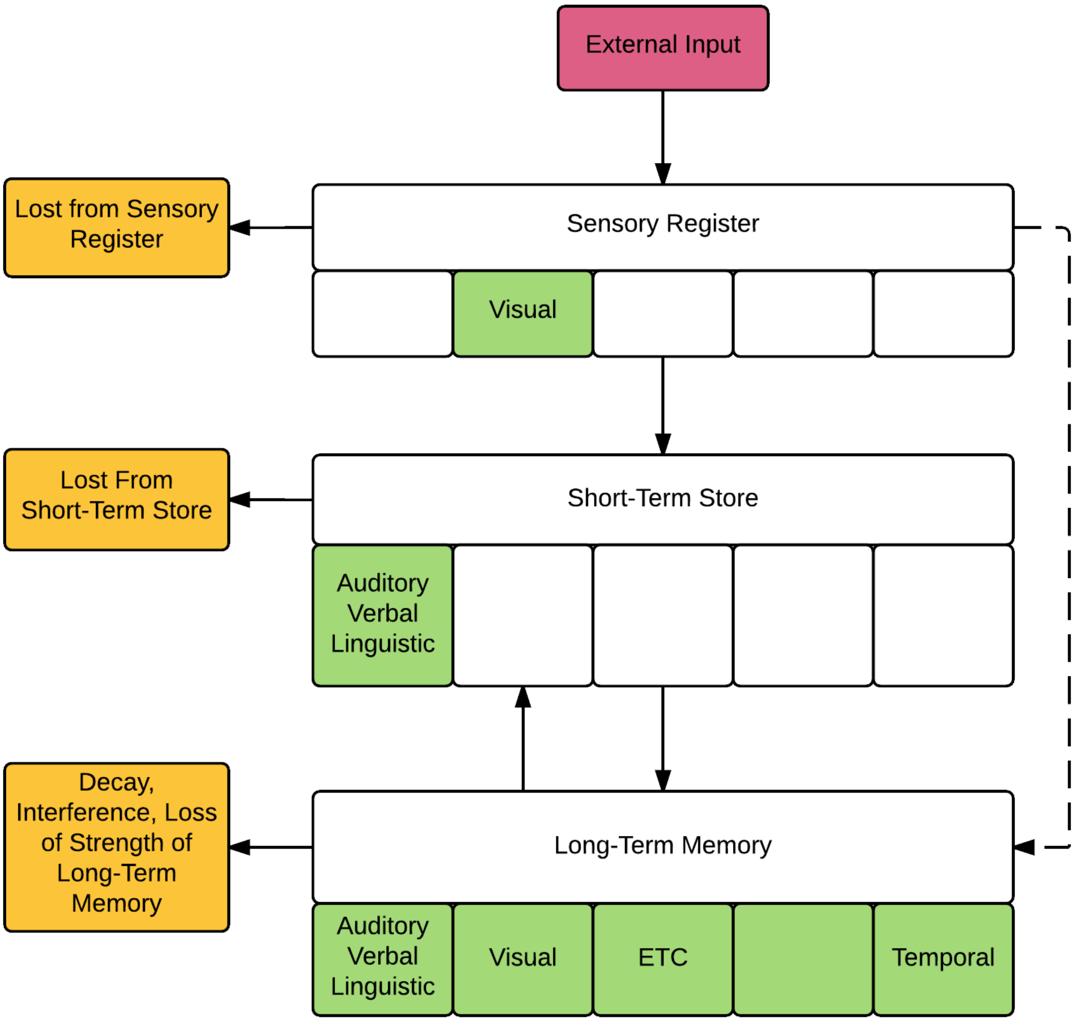

Figure 4 Structure of the memory system[60]

The information processing model later emerged as a multi-component sequential series with a more circular approach (Figure 5). The information processing model is used in education research to explain the interactions between attention, working memory and long term memory and their effect on learning.[61-64] The multiple components are a) a stimulus such as events and observations b) attention c) a working memory function/ working space d) long term memory storage and e) a response.

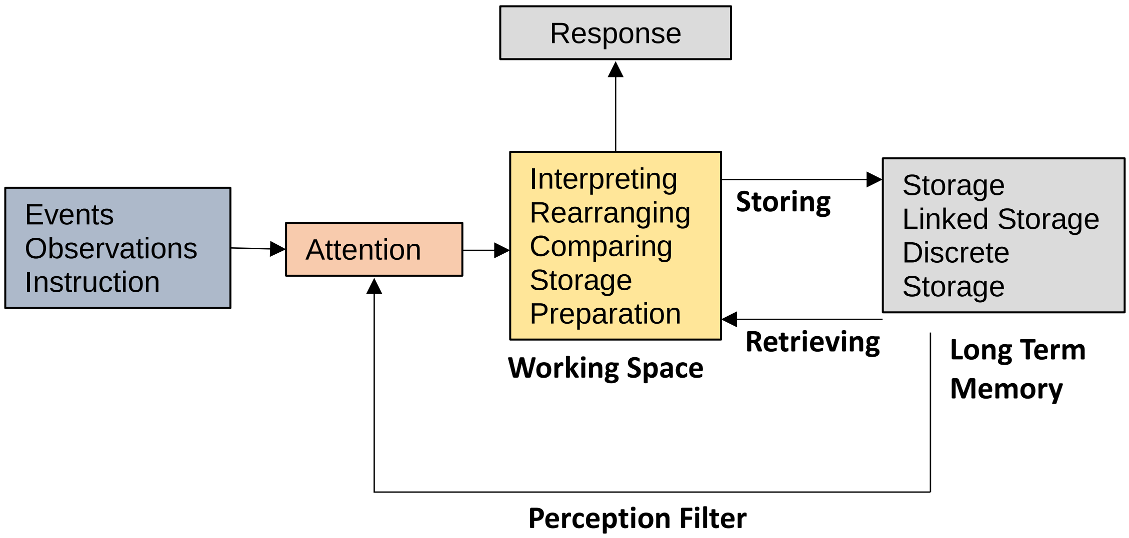

Figure 5 A model of learning and memory organisation in information processing[61]

The model represented in Figure 5 states that for successful learning to occur an individual requires an efficient attention/perception filter, working memory and long term memory. The perception filter is required in order for an individual to select important information for their learning. This information is drawn from stimuli whilst learning and is perceived by an individual's senses. After the information has been selected through perception and attention filters, working memory processes the information from the stimulus and long term working memory and supplies a temporary store for information. Long term memory in this model is a large repository of knowledge, attitudes and skills. If sense is made from the information in working memory then it is stored in long term memory. The further addition of a perception filter loop over the Atkinson and Schiffrin model fits better with the Gestaltist theory of learning[65] and Ausubel[66] who state that the most important factor in learning is using information you already know or understand.

There are limitations placed upon the learning processes through this model. As previously discussed in section 1.1.4 working memory has a limited capacity and under this model, if there were too much information to processes before sense could be made of the information then the individuals processing system is overloaded. Similarly if the processing requires complex processing then system may once again become overloaded.

Five areas of research have been investigated using the information processing model[61]

a) The function of language in science education
b) Problems of learning and understanding in the laboratory
c) Science learning assessment
d) Multiple level learning and
e) Problem solving (this will be discussed in section 1.3)

1.1.6.1 Language and the Information Processing Model

The use of language in sciences has been studied using the information processing model, predominantly by Cassels[67] and later by Selepeng.[68] Cassel suggested that language held in the long term memory store would influence perception filters and working memory. Cassels set out to establish what vocabulary might cause misconceptions in learning and, as such, effect alternative frameworks.[67] Alternative frameworks are the alternative understandings an individual has in their long term memory about a situation. Cassels isolated more than 100 words that could cause misconceptions in science education. These misconceptions could continue into higher education. Terminology that Cassel identified were words like 'volatile' which could be interpreted by students to mean unstable, explosive, or easily vaporised. In this example all of them realistically could be associated with a chemistry concept. However, two of the students' understandings could lead to alternative frameworks from that intended. For example a passage of text may describe a chemical as being volatile with the intention that the chemical is easily vaporised. However, the student has two additional interpretations of the word volatile to choose from, including unstable and explosive. The student could quite readily develop an alternative understanding to that intended in the passage of text they have just read, and thus develop an alternative framework for understanding the chemical concept. Furthermore, Cassel found that the language issue was greater in students whose first language was not English.

Selepeng, instead of looking at the effects of long term memory, looked at working memory.[68] Selepeng conducted digit span and reverse digit span tests, firstly giving participants words in their native language and then followed by a second non-native language.[69] The working memory space was on average 1.6 units (20%) less in the second language than in their native tongue. Thus students were handicapped in their learning process by the processing demand of the second language. This could be due to the translating component requiring working memory space which could not be allocated to the understanding of science.

1.1.6.2 Problems in Laboratory Work and the Information Processing Model

Some studies suggest that little cognitive gain is achieved by undergraduate students participating in laboratories at university level.[62, 70, 71] Most of these studies suggested that although undergraduate students do gain the necessary laboratory skills and techniques, they are incapable of linking the theory they learn in lectures to their laboratory work. It has further been identified that written and verbal instructions, unfamiliar chemicals and equipment and writing lab reports occupied space within working memory that could have otherwise been used for cognitive processes. Wham[70] noticed that students were often overloaded with the demands of recalling knowledge when conducting laboratory experiments. Letton[71] discovered that students struggled with the over load of instructions, and that a reduction in performance in the laboratory occurred when there were too many instructions. This was hypothesised to be in part due to limitations in working memory. Sleet and Vianna[62] noticed that using pre-laboratory exercises and mini-projects improved lab performance and familiarity with experimental processes. This work was continued by other researchers who specifically designed the laboratory exercises with pre-laboratory components.[71-73] It is seen that students use instructions more like a recipe instead of understanding the processes that are involved. However, this observation does fit with the confines of the information processing model. The pre-laboratory exercises were designed to get students to think about the experiment they were conducting by making them plan parts of the experiment and activating long term memory. The activation of the long term memory meant that students were more easily able to think about relevant parts of the laboratory class by freeing space within their working memory.

1.1.6.3 Science learning assessments and the Information Processing Model

El-Banna and Johnstone's work suggests that as the complexity in test questions increases there is a rapid fall in performance due to limitations in working memory.[74] So if the demand of the test question is within the working memory limit of students then the science is being assessed. However, if the demand of the test question lies outside the working memory limit of the individual student then the test question is measuring the working memory space. It has been noted that some students are able to overcome the limits of working memory space using techniques such as chunking or breaking the task into small sub-tasks. [61]. Chunking is a memory process where lots of complex information is collapsed into one piece of information or a “chunk.” An example of this is remembering a phone number; where the phone number is remember as one piece of information rather than 11 separate numbers. The chuncking model has its grounding in a Gestaltist Law of Proximity (items that are close together in space can be perceived as a group)[75] and Similarity (items that are similar to one another can be perceived as one group).[75]

1.1.6.4 Multiple level learning and the Information Processing Model

It has been recognised that overloading of the working memory in the information processing model can occur due to the very nature of learning science.[76, 77]. In science education, students are not only presented with the object, such as a bottle of alcohol (macro), but also the molecular description (sub-micro) and its atomic or molecular formula or equations (representational). Figure 6 shows the distribution of the three conceptual levels available within a topic as described by Johnstone.[61]

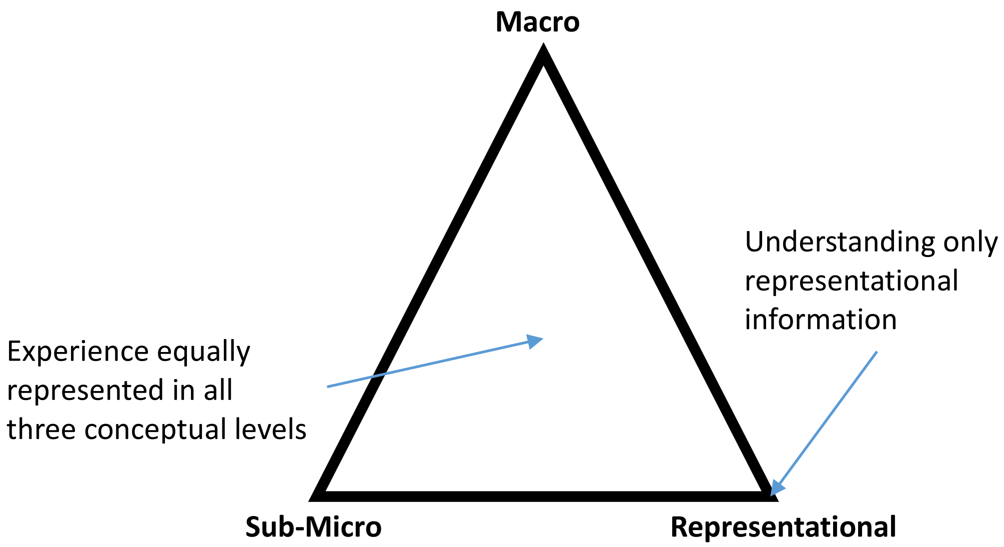

Figure 6 The three conceptual levels of chemistry.[61]

Figure 6 suggests that at the corners of the triangle 100% focus of a subject is assigned to that type of concept. For example, the triangle represents a concept in chemistry and each point of the triangle represents the different types of information that is required to understand the chemical concept. When a person only understands representational information about a chemical concept they are considered to be at the triangle point labelled representational. As a person begins to learn the chemical concept, they start to learn the different types of information and move around the triangle as they become more competent with the chemical concept. Once a person has transitioned to the centre of the triangle they are considered to deal with all sub-micro, macro and representational information about a scientific concept. Although it is easier for individuals with experience in chemistry (such as academics and graduates) to move around the triangle in Figure 6 without risking an overload of working memory, the same cannot be said for students. Students not only run the risk of overloading working memory due to simultaneously engaging with material at the three conceptual levels, but also increasing the risk of developing or using alternative frameworks. In recent years, the model of three conceptual levels of chemistry has begun to incorporate a fourth level. Mahaffy suggested the addition of the human element as an attempt to alleviate the concerns of limited public understanding of science.[78] With the addition of the fourth element the planar triangle is transformed into a tetrahedron of learning levels (**Error! Reference source not found.**), suggesting that science exists in a human context and students must link real life applications to their theoretical knowledge. Once the human element is added to the model the complexity increases and overload may be more of a problem.

1.2 Testing Cognitive Function

There are many methods of testing cognitive function including mental reasoning tests, mental flexibility and perception awareness tests. Problem solving is a popular field of research, especially in science education. Two cognitive functions have been identified as being important for solving problems and will be discussed further in this section. The two discussed will be M-capacity and field dependence/independence.

1.2.1 M-Capacity

There appear to be many factors that can result in overloading of the working memory space, including large technical vocabulary, holding numerous new pieces of information and large amounts of content.[69, 79-82] However, more recently researchers have discovered a link between an individual's M-capacity and successful outcomes in problem solving.[83-88] M-capacity is the measure of working memory developed by Pascual-Leone who viewed it as an activated component of long-term memory. Sometimes it is used synonymously with working memory.[89] However, each are derived from separate conceptual theories. Working memory, as previously stated, relates to a limited capacity system responsible for storage and integration of information performed during cognitive tasks.[90] although they may be considered complementary.[91-93] Many examples in literature confuse the difference between a task requiring integration of cognitive tasks and a task that saturate an individual's M-capacity.

In fact, data suggests that individuals with a high M-capacity perform better on tests[86] with a marginal increase on recall tasks.[94] Johnstone and El-Banna [88] support that even individuals with low M-capacity can still successfully tackle problems and learn, however it would require additional learning techniques.

Currently a number of methods are available for assessing M-capacity including certain span tasks[95] and figural intersection tasks.[96, 97] The span test comes in many different versions including counting span test, backward digit span test and the backward word span test. Each of these tests requires an individual to process an increasing number of pieces of information in their head (such as the number of specifically coloured balls in a visual stimulating pattern). The person can be asked to recall the information (span test) or recall the information in reverse order (reverse span test). These differ from working memory span tests as they always require a processing component. The Figural Intersection Test (FIT) is a 36 item test which assesses a spectrum of M-demands (X= between 2 and 8) where each test item presents two sets simple geometric shapes, one called the presentation set and the other the test set. The objective of each test item is to identify the area of common intersection of the shapes in the test set. The validity of the FIT test as a measure of M-power (M-capacity) has been validated using techniques such as latent class analysis,[98] factor analysis and theory-guided task analysis.[99-103] Although the three approaches to validating methods for assessing M-capacity are slightly different, there is a correlation between the two styles of tasks (span test and FIT test), and they are validated as assessing M-capacity.[97, 104]

The theory of M-capacity states that a central attention system results from interactions of four different functional capacities which are called mental attention operators. The four areas are denoted through capital letters; E, M, I, F. E stands for the executive processes and schemes that monitor the regulation of attention. M stands for mental capacity which is a capacity attentional resource initiated to an individual's schemes to derive the intended performance. I stands for the central attention interrupt, working in direct competition with mental capacity, reducing the codetermination of the intended performance. F acts as a unifying functional attention, through a neo-Gestaltist perspective, functioning as a binding mechanism for overall attentional performance and linking similar activated schemes. The neo-Gestaltist perspective identifies the manner in which individuals are able to acquire and maintain meaningful understanding through the complex interactions of various stimuli despite the apparent chaos of the world. This means that a unifying functional attention, F, is able to attend the individual components of a task in order to complete the entire task. Although this co-dependence of the four operator functions exists and contributes to a score for the FIT, the main design of the test is to assess the M-operator function. The power of the M-operator is determined through the number of distinct schemes that can be simultaneously processed. The scores for the M-operator increase with age through the neo-

Piagetian cognitive stages[103, 105-108] and have been established internationally and cross-culturally.[108-113]

1.2.2 Field Dependency

The concept of field dependence/field independence originates from Witkin,[114-118] and has been predominantly used in education.[119-122] Field dependency is explained as:[114]

- Field independence: The individual can analyse key information in an organised field and separate the key components from its context
- Field dependence: The individual struggles to separate key information in an organised field, and readily accepts the dominating context.

It was also noted that individuals that categorised as field independent perceived themselves as separate from their environment, resulting in an analytical cognitive style. A more analytical cognitive style will seek to analyse organised systems or provide organisation to a disorganised system, or in the extreme, impose a different system onto an already organised system.[114, 116, 123]

Participants who display field dependent characteristics are less able to distinguish between or recognise stimuli, perceiving the situation as it is rather than analysing and restructuring its components. Field dependent individuals will accept the dominant message in the field due to the salient but irrelevant information. Thus, they perceive that the current organisation of the field is optimised.[114, 116] However, field dependent individuals are considered more social, with greater intuition to their environment and the social groups it contains, seeking occupations that involve contact with people.[117, 124]

The differences between field dependence and field independence are best summarised in Table 4[125, 126] which identifies the key characteristics of the individuals.

Table 4 Characteristics of Field Dependent/ Independent learners[125, 126]

Field Dependence	Field Independence
Perceives and approaches things globally.	Perceives and approaches things analytically.
Experiences in global fashion and adheres to structures as given.	Experiences in an articulate fashion and imposes structures of restrictions.
Makes broad general distinctions among concepts and sees relationships.	Makes specific concept distinctions and little overlap.
Social orientation. Tend to be influenced by peers.	Impersonal orientation. Less likely to seek peer input.
Learns material with social content best.	Learns social material only if have to.
Attends best to material relevant to own experiences.	Interested in new concepts for their own sake.
Requires externally defined goals and reinforcements	Has self-defined goals and reinforcements.
Needs organisation provided.	Can self-structure situations.
More affected by criticisms.	Less affected by criticisms.
Uses spectator approach for concept attainment. Attend to salient cues first, regardless of relevancy.	Uses hypothesis-testing approach to attain concepts. Sample more cues, regardless of saliency.
Extrinsically motivated.	Intrinsically motivated.

There are a variety of tests that can be used to determine field dependence but this literature review will focus on the GEFT test and its validity, which is the test used in the subsequent research. The GEFT test is a 20 item test that requires individuals to identify a specific hidden shape in a matrix of shapes.

Although the GEFT test used to determine field dependent/ field independent individuals are very well tested, it should be noted that additional factors can influence test scores on the GEFT. These factors are age, gender, socio-economic status, childhood upbringing, hemispheric lateralisation.

Age: Children are considered to be field dependent, transitioning to become more field independent as they mature into adulthood. Adults are more field independent. However, as adults become older they gradually become more field dependent.[127]

Gender: Studies have shown that male participants achieve higher scores than their female counterparts suggesting that they are more field independent. However, after statistical analysis the influence of gender is relatively insignificant.[128]

Socio-economic status: students who are from lower socio-economic class tend to display more field dependent characteristics than students from higher socio-economic class.[129]

Childhood Upbringing: Studies have shown that households where strong obedience to parental authority and external control were emphasised, participant displayed greater field dependent characteristics.[130]

Hemispheric Lateralisation: Hemispheric Lateralisation is the distinction between tasks that are operated by the left and right hand side of the brain. Where a particular hemisphere is seen to be more heavily involved that hemisphere is deemed more dominant. Tasks that are affected by lateralisation of the brain are language[131] and handedness.[132] Studies have shown that left handed individuals show greater field dependence than right handed individuals.[133, 134]

The GEFT test assesses the participants ability to make judgements and separate information from specific distractions.[118, 135, 136] Due to its success at identifying independency characteristics, field dependence-independence has been used to assess school achievement,[137] additional language learning,[138] sports performance[139] and social-cultural functioning.[140] The particular focus of GEFT in assessing school achievement and problem solving[119-122] makes it an important tool to determine whether field-independence is important for solving problems.

The validity of the test has been assessed through a variety of methods such as test correlations between the embedded figures test (EFT[127]), the rod and frame test (RFT[141, 142], sometimes the Portable rod and frame test is used, PRFT) and the degree of body articulation which is assessed by means of a scale (ABC) applied to human figure drawings.[143, 144] All three of these tests have been shown to assess field dependence/independence. Table 5 demonstrates these correlations:

Table 5 Validity Coefficients for the GEFT When Compared Against the EFT, PRFT and ABC[127]

Population	N	Criterion Variable	r with GEFT score*
Male Undergraduates	73	Individual EFT, solution time	-.82
Female Undergraduates	68	Individual EFT, solution time	-.63
Male Undergraduates	55	PRFT, error	-.39
Female Undergraduates	68	PRFT, error	-.34
Male Undergraduates	55	ABC, degree of body articulation	.71
Female	68	ABC, degree of body	.55

Undergraduates		articulation	
*r’s with the EFT or the PRFT should be negative because the tests are scored in reverse fashion			

The values in Table 5 show the evidence from the validation studies of the GEFT. The correlations between the GEFT and the EFT are reasonably high, in particular for men. Correlations between the GEFT and the PRFT are toward the lower end of the correlation range, and typically resemble those correlations between EFT and the PRFT tests. The correlation between the GEFT and the ABC are towards the higher end, particularly for men, once again demonstrating similar correlations between the EFT and the ABC tests. This would suggest that EFT, GEFT and the ABC are assessing similar causal dis-embedding effects, whereas the PRFT is assessing a separate cognitive function. This would follow the literature which would suggest that the PRFT is also effected by spatial restructuring.[114, 145]

1.3 Solving Problems

Problem solving has been of interest to professionals and researchers for many years. The key question to be asked at this stage is what is problem solving? Krulik and Rudnick describe a problem as “a situation quantitative or otherwise, that confronts an individual or group of individuals, that requires resolution, and for which the individuals see no apparent or obvious means or path to obtaining a solution,”(pg 3)[146] Hayes defined a problem as “whenever there is a gap between where you are now and where you want to be and you don’t know how to find a way to cross that gap, you have a problem.”(pg i)[147] Therefore, problem solving can be described as “the means by which an individual uses previously acquired knowledge, skills and understanding to satisfy the demands of an unfamiliar situation. The student must synthesise what he or she has learned, and apply it to a new and different situation."(pg 4)[146] Problem solving has also been described as "what you do when you don't know what to do."(pg 1)[148] The definition of problem solving is further complicated by Anderson's definition which is "a goal-directed sequence of cognitive operations."(pg 257)[149] However, generally it is accepted that a problem must be unfamiliar in some way, demand cognitive processing and that it is the unfamiliarity which separates problem solving from an exercise. So is a unified theory of problem solving possible and is it possible to understand the strategies employed in problem solving? Bodner believes "it is possible to construct a unified theory of problem solving. I [he] have done so… Unfortunately, I'm afraid our unified theories will differ significantly from one another."(pg 21)[150] This situation is partly due to the differences in defining individual components within any theory of problem solving.

Furthermore, researchers can't even agree on the term "problem". Some believe that exercises are a subset of problems, whereas some believe that exercises and problems are mutually exclusive, differing in difficulty and complexity.[151] A further complication is whether using solely algorithmic processes can be used in solving problems and whether using solely algorithmic processes demonstrates learning and understanding. The types of problems used in examinations in the current education system, particularly pre-higher education, are typically algorithmic in nature because the questions assess familiar methods, altering only the data input.[152] A definition of algorithms is "rules for calculating something that can be followed more or less automatically by a reasonably intelligent system, such as a computer"(pg 17)[153] and generally require lower cognitive functions than problems using non-algorithmic processes[154, 155] In particular "the existence of a problem implies that the individual is confronted by something he or she does not recognize, and to which he or she cannot merely apply a model. A problem will no longer be a problem once it can easily be solved by algorithms that have been previously learned."(pg 3)[146] With this definition in mind one may eliminate from problem solving any task that can be solved solely through an algorithm, as it demonstrates only operational processes rather than conceptual understanding. It could be the presence of well-defined algorithms combined with prior knowledge that results in a problem turning into an exercise.[74] This statement is supported by Bennett who suggests that many calculating-type questions in examinations are masquerading as problem solving. Examinations predominantly include 'easy to set, easy to mark' questions. Bennett further states that examinations focus on regurgitating of information or 'soft' calculations where the questions are the same year to year altering only the input data.[152]

There are many different theories attached to the constituent stages of problem solving, although most submit to a multiple stage approach,[146, 156, 157] initialised with an "understand the problem," and concluding with a "reflection" component.[158] The overall objective of educational problems is that problem solving develops theory and practice,[146] creativity;[159, 160] enhances a complete and organized knowledge base and develops transferable skills in order demonstrate conceptual knowledge to others.[161-165] Kendall & Fischler state that the problem of applied problem-solving research are the "operationalisation of actual problem-solving skills" and the "effectiveness and competency" of problem solving.[166] Furthermore the measurements for capturing data for applied problem solving are verbal/think aloud and observational.[167]

In 1993 Johnstone attempted to subcategorize the different types of problems encountered in science education based around altering three different variables, as shown in Table 6. The three variables were the data in a problem, the method of tackling the problem and the outcomes/goals of the problem. As a result of altering the three variables, Johnstone states eight possible types of problem, the first, type 1 with given data, familiar method and closed outcomes, equating to routine exercises requiring lower order cognitive skills, rising to type 8 problems with incomplete data, unfamiliar method and open outcomes, which resemble real life complex problems that graduates may encounter in the work place.

Table 6 Classification of problems.[85]

Type	**Data**	**Methods**	**Outcomes/Goals**	**Skills Bonus**
1	Given	Familiar	Given	Recall of algorithms.
2	Given	Unfamiliar	Given	Looking for parallels to known methods.
3	Incomplete	Familiar	Given	Analysis of problem to decide what further data are required.
4	Incomplete	Unfamiliar	Given	Weighing up possible methods and then deciding on data required.
5	Given	Familiar	Open	Decision making about appropriate goals. Exploration of knowledge networks.
6	Given	Unfamiliar	Open	Decisions about goals and choices of appropriate methods. Exploration of knowledge and technique networks.
7	Incomplete	Familiar	Open	Once goals have been specified by the student, the data seems to be incomplete.
8	Incomplete	Unfamiliar	Open	Suggestion of goals and methods to get there; consequent need for additional data. All of the above skills.

Although some of the statements in Table 6 conflict with previous comments made by Bodner relating to problem solving (if a method is familiar or routine it can't be a problem), researchers predominantly use Table 6 to demonstrate problems/exercises at the two extremes. The type 1 problems under Johnstone's definition would be consider exercises and algorithmic in nature. The type 1 problems are considered exercises because all the data is provided, the method of calculating the solution is familiar to the individual and the there is one discrete answer. Type 8 problems in Johnstone's definition would be considered open-ended questions. Type 8 problems are considered open ended because the data provided is incomplete, the method of calculating the solution is unfamiliar and the outcome to the problem is open ended whereby no predetermined outcome is expected.

In problem solving it has been identified that learners have a specific M-capacity (X)[64] which is the maximum number of tasks an individual can process and each problem has required processes and functions that must be completed to achieve a solution. Therefore, a student is "successful in solving a problem if the problem has a Z-demand (load demand) that is less than or equal to the subject's X-capacity (M-capacity)."(pg 8)[168] Using an information processing capacity model, a direct correlation exists between the increasing complexity of the problem and a reduction in performance.[169, 170] This was shown in a study conducted by Pascual-Leone and Smith who showed, in 1969, that under a Piagian paradigm, as the complexity of the task increased children aged 7 and 8 years old were still able to process the load demand of the problem, whereas children who were younger were unable to do so.[169] Even a small alteration to load demand can overload M-capacity.[171] This would mean that if the load capacity of an individual is X=5 then the individual is capable of processing a problem with a complexity of 5, and becomes quickly saturated if the demand of the problem exceeds 5. Figure 7 displays this concept whereby the individual performance decreases as the complexity of the problem increases, depicted by Johnstone and El-banna.[88]

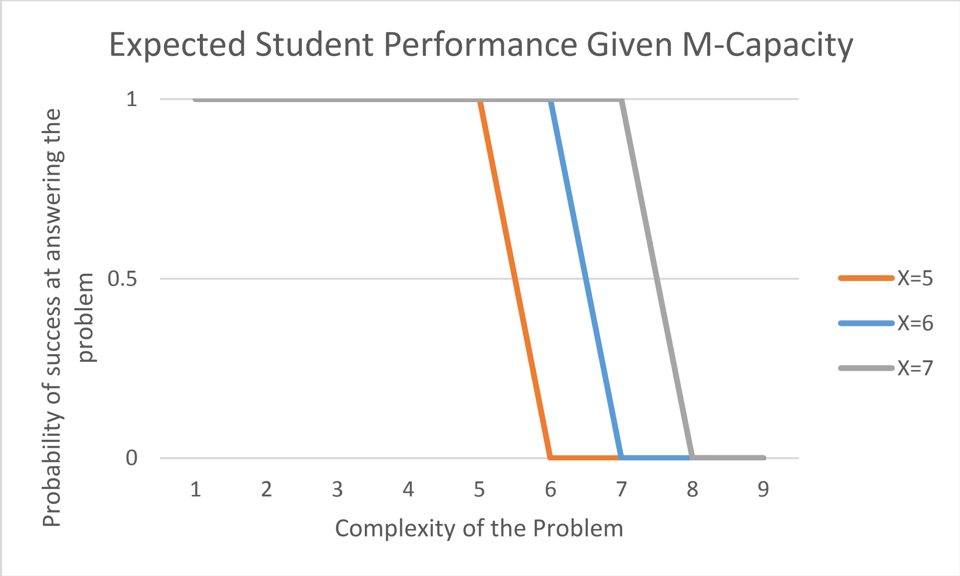

Figure 7 Diagram showing probability of success at answering the problem as the problem increases in complexity with load capacity X (redrawn from Johnstone and El-Banna, 1986)[74]

The effect of specific load capacity of a problem was observed further by Johnstone and El Banna who investigated the relationship between increasing complexity of a problem and the performance by students. The study required participants to answer a series of questions in increasing complexity. The complexity of each problem was agreed on by a committee of researchers. Johnstone and El-Banna expected that as the complexity of the problem increased, the performance of students would gradually decrease. However, when the percentage success rate data was plotted against complexity demand of the problem, the researchers observed sudden fall off in success at or around the theoretical capacity of the individual, that is when the task demand exceeds the capacity of the individual they are no longer able to perform the task. From the data collected Johnstone and El-Banna observed the same shape as in the theoretical diagram observed in Figure 8.[88] Figure 9 shows a representation of the data Johnstone and El-Banna collected (data plots taken from reading values from published graph).[88] The graph clearly shows that as the complexity of the problem increases, student success rapidly decreases, in a similar method as predicted under cognitive load theory (Figure 8) and M-capacity tests (FIT scores)

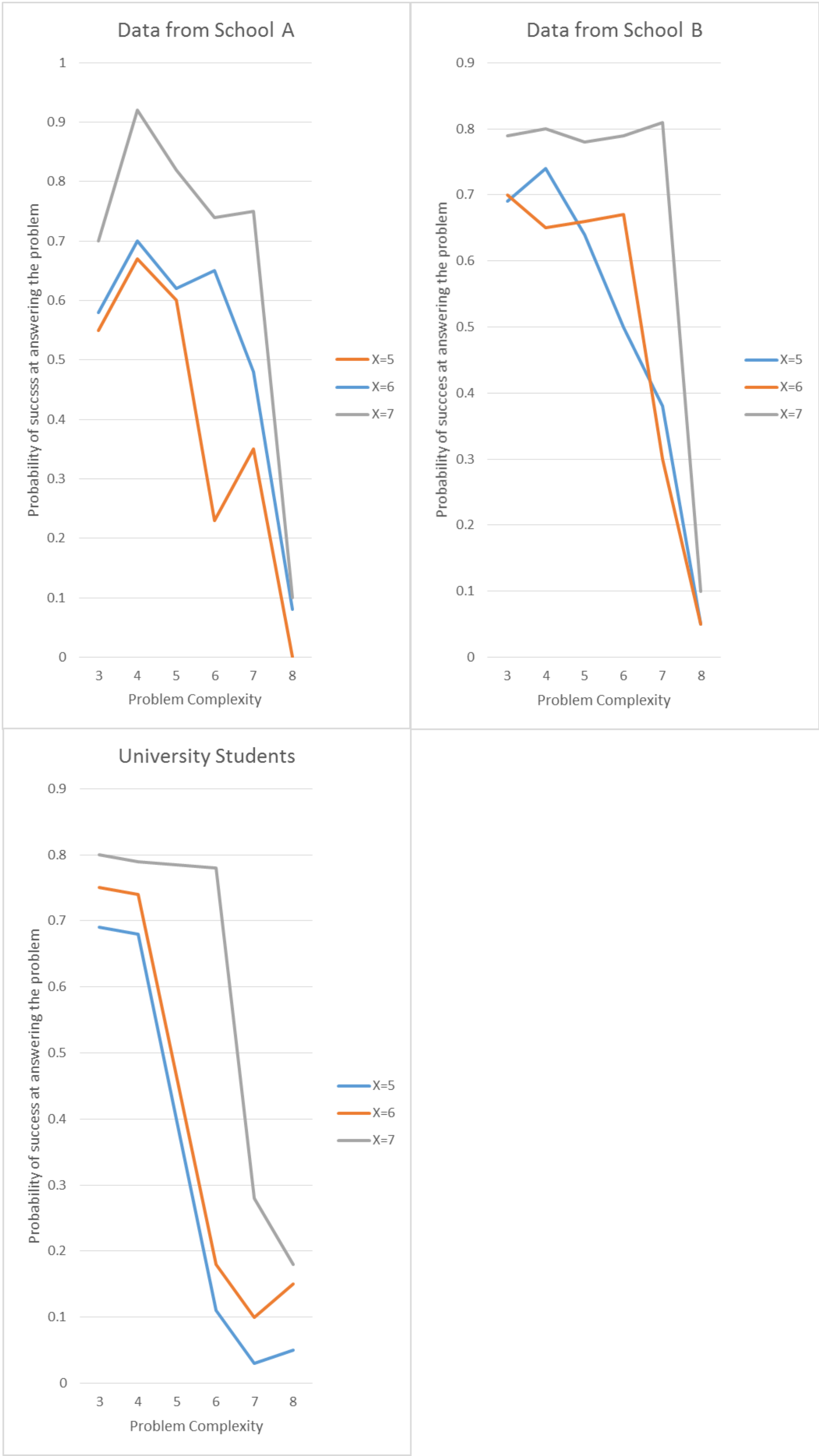

Figure 8 Visual representation of the data collected by El-Banna and Johnstone comparing problem complexity and success. Redrawn from Johnstone and El-Banna.[74]

Niaz and Robinson looked at the increasing M-demand of chemistry problems and how it affected student performance. What they noticed was that when the ‘logical structure’ of the problem was altered, by through altering concrete and formal operational learning, there was a significant alteration in performance on the whole task, to the extent that the increase in complexity of the problem was no longer beneficial to the learning process of the individual.[171] This was further shown in a study conducted by Kellett[172] who observed a difference in performance of recall for organic structural formulas and equations when they were presented to students. Kellett noticed that some responses received 100% recall success, whereas similar structures under a different format often received poor recall. Scripts were analysed and it was noted that students got more errors to the right hand side of the structure than the left. This was because they ‘read’ the structure from left to right memorising each chemical symbol. As the number of symbols increased, the number of correct responses decreased. This was because the load-capacity of the question saturated the working memory capacity of the participant.

1.3.1 Expert-Novice Studies

Understanding changes in problem solving ability that occur as expertise develops has been of interest to cognitive psychologists, not solely because of the interest in what makes an expert, but because of the implications for research-driven teaching practice.[173] Gaining better insight into how experts tackle problem solving could create better training and education programmes.[174-179] Most of the early literature focuses on process development using rules of reasoning which “might be acquired as transferable habits of thinking.”(pg 10)[180] However, in many of the studies participants were required to solve abstract problems and puzzles, which had little bearing on the knowledge specific tasks often faced in problem solving. Larkin *et. al.* focused on knowledge prerequisites which distinguish expert thought.[181] Often, superior problem solving skill is described by terms such as 'talent', 'intuition,' or 'judgement' which has little to no bearing on the 'experts' performance other than they have greater experience with the situation.[181] Larkin *et. al.* further state that although a large repository of knowledge is a 'prerequisite' to being an 'expert,' it is the networked connections between pieces of information and the speed of recall that create complex schemata signifying 'apparent intuition.' Larkin *et. al.* compared this recall process to looking up words in a dictionary, whereby the expert's 'indexed node-like structure' can identify the information required because they understand the patterns of recall required to answer the problem, similar to letter order in a word.

De Groot conducted a famous study looking at how expert chess players found the best moves,[182] although is often misquoted.[173] An expert chess player may have some innate ability to play chess. However, their ability to remember the position of 25 or more chess pieces is based around recognising patterns of placement rather than a 'remarkable' memory for detail. The familiarity of the positions reduces the load on the working memory, and it appears the individual can memorise the piece positions. The appearance of the individual memorising pieces of information in a pattern of understanding are called schema. The schema enable the individual to perform actions previously completed based around their prior experiences, reducing working memory load. Evidence of the use of schema is further supported because when the pieces are placed randomly, the 'experts' perform similarly to the 'novice' players when choosing the appropriate moves, as the load on the working memory is similar, with little to no prior experience of how to perform.[181-183] However, it should be noted that in de Groots study[183] all participants in his 'novice' study were candidate masters (very good chess players) with an Elo rating (classification of chess ability) of between 2200-2000 (average chess player 1500, grand master players at least 2500). Gruber *et. al.*[184] furthered de Groots study with novice chess players (participants with no Elo rating, but an understanding of the rules of chess) and found that Grand masters did perform differently than their novice counterparts. Gruber *et. al.* showed that although participants spent a similar amount of time on solving the chess problem, Grand masters were better at thinking about further moves ahead for each solution, and the quality of the solution was greater.[184] Although the de Groot/ Gruber case study is not science-related problem solving, it does identify differences between expert and novice problem solvers within a particular discipline.

Chi *et. al.* were focused on the functionality of how knowledge is structured.[185] They focused on the characterisation of problems and how experts and novices categorise them. Experts organise "around principles and abstractions that subsume,"(pg 18)[180] the problems character whereas novices organise "around the literal [characteristics] explicitly given in the problem statement."(pg 18)[180] Expert problem solvers are less confined by the concepts stated in the problem and draw on further experiences and schema in comparison to novice problem solvers. Experts also seldom focus just on the quantitative concepts, but are able to qualitatively analyse previous schema. The issue arises that problems are solved quantitatively rather than qualitatively, even though the latter precedes the former. Equations might symbolise concepts for quantitative analysis, but the symbols must be connected to a "richly elaborated mental construct,"(pg 22)[37] which by their very nature is qualitative.

1.3.2 Problem Solving in Science

Researching problem solving in chemistry is not a new activity. However, as previously stated in Section 1.3, the largest obstacle associated with the field of problem solving research is unifying the terminology of 'problem solving'. Some research in chemistry education has centred on the difference between closed and open-ended problems. Reid and Young believe that many problem solving tasks in chemistry courses tend towards algorithmic problems, which ill-equip graduates to tackle 'real-world' problems.[186] Glover *et. al.* state that the most important real-world problems are ill-defined, comprise of multiple components and contain open-ended outcomes.[187] Glover *et. al.'*s definition of 'real world' problems mirrors the type 8 problems proposed by Johnstone. These open-ended problems in chemistry have limited, but no single, method of deriving the solution and outcomes. In early studies, chemical problems were defined on two dimensions; the solution they required and the source of the information required to answer them.[188] These early definitions sub-divided problems along a sliding scale from chemical puzzles (where there is a unique answer and information provided in the problem) to higher level research (where there may not be a unique answer and data acquired through observations or experimentation).

In many chemistry examinations, questions are described by many examiners as assessing problem solving skills. However, under greater scrutiny the observer gains the impression that the questions solely demonstrate an application of knowledge to a routine task. These problems would be categorised as algorithmic, as they require only the implementation systematic processes.[186]

The development of theories of problem solving started in the 1940s with experimentation centring around content-free and game-like processes with participants developing solutions with little specialist knowledge.[156] Polya proposed a theory for a model of problem solving that incorporated four components to be successful; understanding the problem, developing a plan, implementing the plan and reflection. Although this is representative of solving mathematical algorithmic problems Polya's model is not suitable for solving open-ended problems.[186] In 1994 Gabel and Bruce reviewed the previous 12 years' literature on problem solving.[189] They identified that problem solving in chemistry was influenced by three main factors; a) the nature of the problem, including the underlying concepts to which the problem is based, b) the individual's learning characteristics, such as cognitive function and knowledge base, and c) learning environments of the problem, including strategies used and individual or group activity.

Using the review article by Gabel and Bruce as a starting point, seven factors have been identified through education research as influencing successful problem solving in chemistry.[189] The seven factors are:

a) Prior experience

b) Prior knowledge base

c) Knowledge and learning

d) Cognitive factors

e) The effects of co-operative group work

f) Use of algorithms and conceptual understanding

g) General strategies and problem solving skills

1.3.2.1 Prior experience and successful problem solving

Experience in problem solving has been shown in various studies to be an influencing factor in successful problem solving.[188, 190, 191] It has been shown that prior experience in conjunction with a knowledge base and emotional connection with the problem are related to the success in problem solving.

Ashmore *et. al.* suggested that problem solving required a network of thoughts that would interconnect the different pieces of information, and isolating the relevant information required to answer the problem.[188] The network links were created by breaking down the problem into discrete pieces that could be reassembled to derive a solution. Ashmore states that the network connections are established through three different methods; a) a statement within the problem itself, b) recall of information in the individual's memory, and c) information derived through reasoning. They further suggested that a deficiency in one of these areas could impede progress in the problem solving strategy. Ashmore *et. al.* concluded that the best chance of success in problem solving stems from a combination of strong background knowledge, knowledge of problem solving strategies and confidence.[188] These conclusions were further supported by the work of Waddlings, who suggested that for educators to better understand their students' problem solving ability they must better understand the network of thoughts constructed by their students.[191]

A study conducted by Frazer and Sleet used a selection of closed-type problems which could be completed using algorithms and calculations.[190] In their study they broke down each problem into smaller parts termed 'sub-problems'. Participants were asked to complete each sub-problem and demonstrated that they were capable of doing so, yet were incapable of completing the full problem when not collapsed.[190] When compared with Ashmore *et. al.* the results suggested that students were not able to develop the networks of interconnecting pieces of information.[188] This manifested itself in those students who were able to answer each ‘sub-problem,’ as not having a clearly defined strategy to tackle the whole problem. Frazer and Sleet fall short of categorical claims, but suggest that lack of confidence may result in an overload in working memory function. The overloading of working memory capacity impedes the student from being able to identify all the steps required to tackle the problem. Furthermore, it would appear that the networking links may also be instrumental in the solving of open-ended problems.[186]

Further to the networking of thoughts, Gayford’s study suggested that students draw on all their prior experiences when solving problems, and not solely information acquired in the classroom.[192] Some of the additional locations students drew on were popular media and books.

Herron and Greenbowe, however, suggest that students struggle to embed their prior experiences to an unfamiliar situation because they lacked the ability of verification. Verification in this case is when individuals are confronted with unfamiliar problems that required analysis of the problem to produce a sensible representation and subsequent use of familiar rules to a new context.[193] However, in their experience students struggle to overcome the lack of ability to verify unfamiliar experiences because they were unable to link prior experience to the new situation.

1.3.2.2 Prior Knowledge and problem solving

Frazer reviewed a selection of articles associated with problem solving in chemistry and, not surprisingly, discovered that to solve problems in chemistry students require knowledge in chemistry.[194] However, further research has suggested that, although students may possess the required conceptual knowledge, they often fail to solve problems in chemistry.[195-198]

Sumfleth demonstrated that students post-16 had basic knowledge of chemical terms and facts. However, they were unable to identify relationships between the information and apply their knowledge to problems.[195] Within this study Sumfelth concludes that although knowledge of terminology is necessary, it is not a sufficient prerequisite to become a successful problem solver. Sumfelths study is further supported four years later by Shaibu who discovered that, although students had the prerequisite knowledge to solve the problems, they still remained unsuccessful.[196] Shaibu concluded that there was a weak link between the conceptual knowledge students possessed and the ability to solve problems.

The study conducted by Adigwe assessed a link between conceptual understanding and the implementation of algorithmic tests.[197] Secondary school participants in Adigwe's study answered five tests and identified four knowledge characteristics that were involved in answering algorithmic problems. The four characteristics were a) attitude to the problem, b) logical thinking ability c) chemistry knowledge and d) numerical literacy. Crucially, students had to have a competency with the ability to think logically and be numerically literate.[197] However, although these characteristics were important for stoichiometric problems, it may not necessarily apply to non-numerical problems.

A further study by Taha *et. al.* investigated the relationship between the mole concept and success at solving stoichiometric problems because students are taught to solve stoichiometric problems using algorithms.[199] The study asked student participants to answer a 14 item test solving stoichiometric problems. This study found that prior knowledge of the mole concept was a greater indicator of success at problem solving than mathematical ability. The study stated that students had difficulty “making sense” of the chemical reaction itself because teachers are teaching their students algorithmic ‘short cuts’ to understand the mole concept.[199]

1.3.2.3 Knowledge, Learning and Problem Solving

As previously discussed in section 1.1.6, sciences are hard to learn, with Johnstone suggesting that it is difficult for students to learn topics if they have to simultaneously use macroscopic, microscopic and representational concept levels.[77] Johnstone’s conclusions were furthered by additional studies that suggest students have greater difficulty understanding sub-microscopic concepts, such as the atomic structure of molecules, which leads to the development of alternative frameworks.[200, 201] This may mean that when students encounter problems that require all three concept levels and in particular sub-microscopic concepts, then these may hinder performance in problem solving.

Lychott studied high school students answering questions about mass in chemical reactions.[202] The evidence they collected suggests that participants who successfully solved the simple mass-mass problems had significantly less chemical knowledge than those who answered more complex problems. Lychott concluded that without of set of predefined rules to follow students could not be expected to successfully answer the chemical problems.[202] In order for students to become successful problem solvers, students must understand the requisite knowledge to solve the problem.

1.3.2.4 Cognitive Factors in Problem Solving

Many researchers over the years have suggested that problem solving skill are depends on, at least in part, the cognitive structure of the individual.[198, 203, 204] In a study by Kempa and Nicholls, chemistry attainment and word association tests were used to ascertain a relationship between cognitive structure (cognitive structures are the basic mental processes used to understand information) and problem solving in chemistry.[204] They found that the cognitive structure of successful problem solvers were more complex than participants who were poorer at problem solving. It was further found that participants that were poorer at problem solving suffered from a lack of abstract thought and understanding.[204] The problems used during Kempa and Nicholls study were all algorithmic/ exercise in nature although they may be applicable to open-ended problems too.

Chandran *et. al.* found that prior knowledge and reasoning skills were significantly related to chemistry performance.[205] However, Chandran also discovered that there was no link between field dependence and M-capacity with respect to performance in answering chemistry problems. This is not a belief held by many researchers in chemical education research because studies conducted by El-Banna[206] and Al Naeme and Johnstone[207] suggest that the extent of field dependence is reflective of chemical achievement, which is again supported by Danili[208]

Niaz carried out a series of studies that concluded working memory capacity, cognitive styles and formal operation reasoning effects the success of individuals at solving problems.[209-212] Niaz identified that in order to balance even simple chemical equations, students had to be operating at Piaget's formal operational level. Furthermore, as the problem demand increased a large M-capacity was required to solve the more complex problems.[213] In a few studies, Niaz links M-demand from Pascual-Leone's theory of M-capacity with Piagetian education theory in chemistry problem solving tasks. One study identified that as the M-demand of the problem increased student performance decreased as a direct result of the increased M-demand of the problem.[210] Niaz showed that M-demand was required for a variety of chemistry problems, not just for balancing chemical equations. A further study by Niaz analysed the links between manipulations in M-demand of chemistry problems through a Neo-Piagetian perspective.[211] The M-demand of the chemistry problems were manipulated by presenting two different tests, one test with all the questions with an M-demand of 7, and a second test in which all the questions had an M-demand of 8. Niaz identified four groups of students emerging from the data as constant, positive, negative and zero.[211] Niaz stated that members of the constant group were able to perform suitably before and after manipulation of the task, and they all scored high on the cognitive predicting tests (FIT, M_f, Lawson test and GEFT).[211] Positive students improved their scores when the M-demand of the problem increased, although this phenomena was attributed to greater training through chunking information.[211] Negative students decreased their scores as the demand of the problem increased. Negative students also scored lower at cognitive predicting tests than the positive students.[211] The last group were identified as the zero group. These participants scored low on all chemistry problems and scored low on the cognitive predicting tests.[211] Another study by Niaz evaluated whether participants who had the same M-capacity but scored as field independent on the GEFT were able to perform better than field dependent individuals. Niaz was also interested to identify through this study whether students with the same M-capacity perform differently when solving chemistry problems with increasing M-demand. Through this study Niaz identified that participants may have the 'structural' M-capacity (M_s, total M-capacity) but operated with a lower 'functional' M-capacity (M_f, used M-capacity).[212] Niaz further states that "science teachers could explore the different situations (e.g. manipulation of the M-demand of an item) which could lead to the optimisation of M_f, However, it is preferable to manipulate the M-demand of an item whilst maintaining its logical structure, rather than to use algorithmic solution strategies."[212] Furthermore, the study identifies that even a small alteration in M-demand of the problem results in poorer performance because students lack the capacity to mobilise their M-power (power of the individuals mental concentration mechanism).[212]

In science education the use of field dependence as a determination of cognitive style with respect to using the information processing model is regarded as important because it is able to assess dis-embedding ability. Two papers that focus on links between field dependence and problem solving would suggest that individuals who are field independent have greater success in problem solving than individuals who are field dependent.[214, 215] Ronning *et. al.* discovered that field dependent students responded more briefly, pause more frequently and 'false start' more often than field independent participants.[215] However, field independent students were more likely to identify key information in the problem more readily and significantly outperformed field dependent students. Therefore, field independence is more beneficial for solving chemical problems. These conclusions are further supported by Al-Naeme and Johnstone.[207]

Vaquero *et. al.* investigated the relationship between Pascual-Leone and Baddeley's models of information processing, and whether either could be used to determine academic performance.[216] In their study they assessed a variety of cognitive factors including working memory (span tests) and M-capacity (FIT). Vaquero *et. al.* identified that scores on Figural Intersection Test (Pascual-Leone M-capacity theory) is a better predictor of performance than working memory span tests (Baddeley's working memory model).[216] However, Vaquero *et. al.* further suggested that span tests are a better predictor for success in languages, whereas the Figural Intersection Test is better at predicting performance on science courses.[216]

Tsaparlis conducted a correlative study between solving novel non-algorithmic physical chemistry problems and cognitive factors.[217] Participants (n=250) in this study were asked to answer tests to measure cognitive factors (Lawson's scientific reasoning test, backwards digit span test, FIT, hidden figures test). Tsaparlis analysed the scores through Spearman's and Pearson's correlation coefficients (Pearson's correlation coefficient was reported as combined estimators based on Fischer's z-transforms) and identified the following:

1. Lawson's scientific reasoning test showed no correlation with problem solving score. (Pearson's ρ=0.099)[217]
2. Working memory test scores showed a weak correlation with problem solving scores.(Pearson's ρ= 0.203**; where **significant to $\rho < 0.01$)[217]

3. M-capacity and Hidden Figures test showed correlations with problem solving score.(M-capacity Pearson's $\rho=0.291^{***}$; Hidden Figures Test Pearson's $\rho=0.320^{***}$; where ***significant to $\rho<0.002$)[217]

This supports the finds by Vaquero *et. al.* who suggested that M-capacity was a better predictor of performance in science than working memory.

St Clair-Thompson *et. al.* investigated the links between M-capacity and the different elements of working memory in chemistry students when they answer algorithmic and open-ended problems.[218] The study involved chemistry undergraduate participants answering a variety of cognitive tests (digit span recall test, reverse digit span recall test, block recall test and the figural intersection test) and comparing these results against success in solving algorithmic problems, open-ended problems and A-level grades. St Clair-Thompson *et. al.* discovered that block recall test was the best indicator of performance in algorithmic problems and A-level results, but the best predictors for success in solving open-ended problems were the digit recall and figural intersection tests.[218] The study is important because it demonstrated that different cognitive styles are required to answer algorithmic problems and open-ended problems.

Overton and Potter explored the potential links between solving open-ended problems and influencing cognitive factors.[219] They asked participants to answer a variety of unfamiliar open-ended. The solutions were marked by assessing success based on the algorithmic, conceptual and contextual demands of the problem. Overton and Potter then correlated assessed scores for the M-capacity and field independence of each participant and noticed early indications that problem solving success may be dependent on field dependency and appeared to demonstrate a threshold effect for M-capacity.[219]

This study would indicate that higher order skills, such as field independency and M-Capacity, may be required for individuals to solve open-ended problems.

1.3.2.5 The Effects of Co-operative Group Work on Problem Solving

Problem solving has been described as an inherently collaborative process[186] whereby individuals combine their knowledge and approaches to accomplish a shared goal.[220].Numerous papers have been published analysing the impact of group co-operation and scientific achievement.[221-224] Qin *et. al.* analysed 43 publications that looked at the impact of cooperative and competitive effects on problem solving success.[225] Qin discovered that a greater success rate was achieved from a collaborative approach to problem solving compared to using a competitive approach in non-linguistic mathematical problems. However, it is uncertain which is preferential for other types of problems.[225] Qin *et. al.* stated that solving ill-defined problems requires the use of creative and novel representations and that groups employing this behaviour are able to share ideas and build a shared representation through group discussion.[225]

Basili and Sanford suggest that cooperative group work focusing on concept tasks not only improves problem solving ability but also alleviates some mis-conceptions in chemical understanding.[226] Furthermore, Basili and Sanford also discovered that students working cooperatively clarify their views on science and discriminate between scientific and everyday terminology. This demonstrates that not only is co-operative learning effective for solving mathematical problems, but also for conceptual problems.[226] Additionally, Tingle and Good discovered that students are able to further chemical understanding collaboratively by using modelling, asking questions of peers and using analogies, which may impact up on problem solving ability.[221]

Cortright *et. al.* investigated the ability to solve novel problems through peer instruction in sports physiology undergraduate students,[227] a concept derived from Lyman's Think-Pair-Share principle.[228] What Cortright *et. al.* noticed was that peer instruction significantly increased the mastery of the original material presented during contact time and, furthermore, participants were able to solve novel problems more successfully with the peer instruction.

Martin *et. al.* looked at the effects of a 12 week problem-based learning (PBL) course on three psychological constructs (motivation, locus of control and self-esteem).[229] Although the research group did not look at the approaches used when engaging with problem-based learning activities, they noticed that participants perceived the additional employability skills, such as working in teams and fostering the development of autonomous study, as an important component of PBL. The research group also noticed that there was a significant increase in the intrinsic motivation of their participants ($p<0.05$), as measured using the academic motivation scale.[229] They further noticed that participants remained extrinsically motivated, looking towards how problem-based learning would impact on their grades. This is not surprising as it has been suggested that later stages of education increase the emphasis on performance of exams rather than learning.[230, 231] Individuals who have to tackle adversity and difficulties when answering problems tend to focus an extrinsic values, and even more in an academic environment where performance is constantly being measured to achieve specific grades and degree classifications.[232] Martin *et. al.* noticed this phenomena reporting that participants said it would "increase career prospects," and there was a "chance to get a good grade."[229] The study further noted that prior to the 12 week PBL course, participants had very low intrinsic scores, because the value participants placed on extrinsic goals was so high. However, after the 12 week course, participants significantly increased their intrinsic focus, enhancing the students' desire "to know." Martin *et. al*. noted that participants noted the benefit of the style of teaching stating "You can come back and get a wider knowledge because more people have gone and done the research."(pg 25)[229]

1.3.2.6 Problem Solving, Algorithms and Conceptual Understanding

Bodner insisted that there is more to solving problems than deriving and applying algorithms in the correct order.[233] However, this is not an opinion shared by everyone. Frank *et. al.* suggested that the use of an algorithm is not necessarily bad, providing quick links between exercises and known procedures.[234] As previously stated in the Taha *et. al.,* study a focus towards using algorithms may, in fact, impede student progress when they encounter real problems.[199] An education process that focuses on algorithmic processes has been demonstrated by numerous studies not to lead to conceptual understanding.[200, 235-238]

Nurrenbern and Pickering compared student performance on gas law problems.[235] Participants were given a traditional written question and a multiple choice question about gases which had no mathematical content. Each question was used to assess conceptual understanding. Nurrenbern and Pickering discovered that participants were able to solve gas problems and limiting reagent problems without requiring understanding of the concepts. They found no link between solving the problem algorithmically and conceptual understanding. Sawrey repeated the same experiment, but used a large cohort of participants and found no difference between students who performed well at solving problems and those that performed poorly when related to conceptual understanding.[238]

Nakhleh conducted a study of 1000 students answering algorithmic and conceptual gas law questions. Although 85% of students could successfully answer the algorithmic problem, only 49% could answer the conceptual problem.[200] Nakhleh and Mitchell demonstrated that although participants were able to answer problems algorithmically, they failed to identify the difference between conceptual and algorithmic questions.[237] and employed an algorithmic approach to answering both types of question. Chiu identified that student conceptual understanding was incomplete, underdeveloped and flawed at various levels throughout the education structure, but these anomalies can relate to specificity of the students geographical location.[239] Chiu further noticed that throughout the Taiwanese education system, conceptual understanding of key chemistry topics can be related to complications between scientific terminology and terminology used in everyday conversation, further impeding conceptual understanding.[239] However, in a separate study Chiu gave 76 eleventh grade students both algorithmic and conceptual understanding questions[240] and noted that students did significantly better at algorithmic questions than conceptual questions in line with other studies. However, they further noted that in their study not many students were considered good problem solvers and poor conceptual thinkers, which in other studies have been suggested as a larger group. Furthermore, most of the students were considered both good problem solvers and good conceptual thinkers, results that are again not reflected by a majority of the literature.[240]

A further study by Surif *et. al.* investigated the relationship of problem solving success and the use of algorithms. In the study 200 participants answered a test assessing their “levels of conceptual knowledge and procedural knowledge”.(pg 423)[241] Knowledge was identified in this study as the "understanding of conceptual ideas and theoretical chemistry, while procedural knowledge is the understanding of how to apply the concepts learned in any problem-solving situation."(pg 418)[241, 242] The research identified a weak correlation between conceptual knowledge and procedural knowledge, and a moderate correlation between problem solving and conceptual and procedural knowledge.[241]

1.3.2.7 General Problem Solving Strategies and Problem Solving Skills

In the late 1980s a large body of literature emerged stating that good problem solving is enhanced by self-confidence, perseverance, enjoyment, positive self-talk and beliefs and values.[243, 244] However, a general shift emerged towards analysing the constituent components of problem solving. Greenbowe states that successful problem solvers exhibit more effective organisation, persistence, evaluate more often, and adopt heuristic and formal operations when compared against less successful problem solvers.[245] In addition to the aforementioned skills, representation continues to be an important component of problem solving.[245, 246] The first step used by successful problem solvers is the initial framing of the problem.[246] This process can be achieved through imaging, inference, decision making and identification of information needed. Hayes suggests that there are two separate modes of representation, the internal and external representation.[147] Internal representation is understanding the information that has been encoded, modified and stored in the brain.[247] External representation is the expression of the processed information to other people, either through drawing diagrams or writing symbols. Bodner and Domin defined internal representation as "the way in which [the] problem solver stores the internal components of the problem in his or her mind."(pg 26)[246] and defined external representation as the "physical manifestation of this information."(pg 26)[246] They state that the characteristic differences between successful and unsuccessful problem solvers is the number of representations that they can apply to the problem and claim that visual representation through the use of models and diagrams can improve performance in problem solving. Returning to Greenbowe's study, it could be possible that there is a link between conceptual understanding and problem representation, where a synergy exists with one effecting the other.[186]

Griffin and Sheehy used a tactical games model to develop problem solvers in middle school physical education students, a model devised by the Teaching Games for Understanding theory.[248] In the theory learning is a constructive process whereby students develop a network of understanding of the games through linking new incoming information with previously learnt information about the games. The theory advocates a shift from content-based educational approaches, instead focusing on techniques where students link tactics and skills in game play, and thus developing skills in problem solving.[248] The original Teaching Games for Understanding theory was a six-stage model that developed decision-making in game situations, starting with an introduction to the game modified to an appropriate level for the learners, and concluding with performance measurement derived from competence and proficiency in students.

Wright proposed more than 10 years ago, that critical inquiry and problem solving in combination with reflective and engagement practices would be the skills required by 'young people' in our modern age.[249] However Wright highlights, as had Bodner for chemistry problem solving, that terminology can quite easily be abused. Some researchers refer to logical reasoning as the attention driven problem solving, reasoning and higher order thinking skills used by learners, stating that learning to think critically is “learning to know when to question something and what sorts of questions to ask.”[250]

1.4 Qualitative Research

Scientists inherently want to quantify their research and are, therefore, far more comfortable using quantitative research. Quantitative research comprises of numerical values that can plot trends and relationships through “testing objective theories by examining the relationship among variables.”(pg 4)[251] Qualitative research provides insight possibly not obtainable by a purely quantitative approach, by processing “questions and procedures, data typically collected in the participant’s setting.”[251] Qualitative research is “a means of exploring and understanding the meaning individuals or groups ascribe to a social or human problem.”[251] Interpretation of data is a key aspect of qualitative research, enabling the researcher to engage in insightful social understanding based on understanding the context. There are many different philosophies of qualitative research which directly influence which theoretical frameworks and methodology are employed. These varying philosophies are referred to as worldviews.

The perception of many in the scientific field is that qualitative analysis holds little relevance, often viewed as speculative and a soft science. Yet over the past three decades qualitative research has begun to embed itself into research papers found in higher impact science education journals such as *Chemical Education Research and Practice*. Qualitative studies have their place in research, although may not be applicable in primarily positivist driven studies. They enable researchers to understand epistemic qualities (beliefs/ feelings and opinions of individuals) for which quantifiable data has little credence and would be overlooked by purely quantitative studies.

1.4.1 Theoretical Worldviews

There are different philosophical approaches to qualitative research which are called theoretical worldviews. These philosophies influence how qualitative research could be conducted. The different worldviews help researchers unearth the 'how' and 'why' discovered in qualitative research. Figure 9[252] displays a selection of nine different worldviews associated with qualitative research.

Figure 9 Different worldviews/ philosophies in qualitative research[252]

The following section will discuss four worldviews commonly used in science and chemistry education research. These four worldviews are positivism, post-positivism, constructivism and pragmatism.

1.4.1.1 Positivism

Positivism holds the view that the scientific approach can be used through interaction between phenomenon of the physical world and humans. In 1982 no fewer than 12 subcategories were identified for this philosophical approach.[253] Most definitions agree that this philosophy asserts the primacy of observation with the pursuit of causal explanation through inductive generalisation[254] or as Smith states “an epistemological approach … which implies the legitimacy of certain methodologies or methods to do ‘things’.”[255]

The philosophy centres around three premises: phenomenalism (discrete pieces of information can be separated from others), unification of scientific theory (scientific method creates theories that are absolute) and neutrality and impartiality (empirical data removes subjectivity).

There are three different perspectives identified as being key stances in positivism. The French, the German-Austrian and American.

The French perspective was developed by Auguste Comte and Saint Simon[256] and is grounded in the search for naturalistic science of society, capable of explaining the past of human kind and of predicting its future by applying similar methods to those adopted in the study of the natural and physical sciences.

The German-Austrian approach roots itself in methodenstreit (conflict in method) which stems from the argument that society is affected by causal explanation or solely through interpretive understanding.

The American perspective developed a similar understanding called instrumental positivism.[257] This is as an initiative theory which believes that instruments of research determine the research question, definitions of concept and therefore knowledge produced. The instruments must be testable allowing for reliability and technical feasibility guiding experimenters through scientific practice and evaluation.

Guba and Lincoln state the purpose of positivism is to verify hypotheses and theories, differentiating itself from post-positivism which seeks to falsify hypotheses and theories[258]

1.4.1.2 Post-Positivism

Post-positivism is sometimes referred to as scientific method, or empirical research. It draws its name from the stage of philosophical development following positivism, challenging the expectation of absolute truth of knowledge from its predecessor.[259] Post-positivism theorises that we cannot be sure (positive) about knowledge in relation to behavioural science in humans. Post-positivists hold similar values to positivists, but relinquishing that causality determines effect and focus more towards identification of causes that influence outcomes. Post-positivists apply a philosophy that the universe is constrained through laws, which require verification and refinement using the scientific method. Five key assumption are associated with this viewpoint:[259]

1) Knowledge is conjectural; absolute knowledge can never be achieved. As such evidence collected is imperfect. A hypothesis therefore can only be disproved, not proven.
2) Research is systemic in making claims, and either refining or rejecting them for other claims.
3) Knowledge is shaped through rational and validated data and evidence.
4) Research endeavours to develop statements which lend themselves to support or describe relationships of interest.
5) Competent enquiry stems through objectivity, where scientists must evaluate methods and conclusions for bias.

The methodology behind this worldview is based on falsifying hypotheses without manipulating external bias and controls.[258]

1.4.1.3 Constructivism

As a theory constructivism allows a researcher to understand how people learn new knowledge and how they make sense of this in the context of previously acquired knowledge. [260-262] The framework allows researchers to better understand how individuals interact with objects and understand 'foreign' objects. [263, 264] The argument is that individuals do not discover knowledge, but construct their knowledge through stepwise processes, with the aim of cognitive development and deep understanding.[265] With many frameworks splinter groups have emerged such as social constructivism,[266] and social constructionism. The difference between the two is subtle but significant:

> "It would appear useful, then, to reserve the term constructivism for epistemological considerations focusing exclusively on the 'meaning-making activity of the individual mind' and to use the term constructionism where the focus includes 'the collective generation [and transmission] of meaning."(pg 58)[267]

Despite their significant differences, the underpinning architecture of the framework are the same.[268, 269] It is also important to note that even though critics accuse constructivists of dismissing reality[262] to the extent of solipsism (the view and theory that the only thing that can be known is self-existence),[269, 270] they are unfounded and misconstrued. Constructivist researchers do not question the presence of reality, but rather the individual's ability to reason its existence and causal effects.[261] There is no absolute answer to reality, rather a judgement that reasoning is true or false.

1.4.1.4 Pragmatism

Pragmatism was developed by Peirce, James, Mead and Dewey[271] and is perceived as the ‘jack of all trades’ philosophy whereby the framework most suitable for analysis of actions situation and consequences are employed rather than antecedent conditions. Rather than focusing on methodology as in instrumental positivism,[272] all approaches are employed to better understand the problem.[273] Pluralistic approaches are used to acquire knowledge about the problem. There are eight viewpoints still used in pragmatism.[274]

1) Pragmatism draws on multiple philosophies making it suitable for mixed method approaches to research.
2) The researcher has freedom of choice meaning they are able to adopt any method, technique and procedure best suited for the research.
3) Pragmatists do not adopt a unified world of absolute knowledge.
4) The truth is based on what works at the time, rejecting thought duality where reality is independent of the mind.
5) The research is focused on what and how to research, centred on the consequences of study.
6) Pragmatist researchers acknowledge that research occurs in social, historical and political contexts and are able to adopt theoretical filters which are reflective of social justice and political policy.
7) Researchers believe in an external world devoid of restrictions of the mind, but believe there is a need to halt questioning of reality and laws of the mind.
8) With no restrictions to philosophical approach or data collection methods, this worldview is suitable for qualitative, quantitative, and mixed method approach.

1.4.2 Theoretical Frameworks

Theoretical frameworks are the different structures around which research can be designed. They are a key aspect in experimental design, as they promote a focus and direction the researcher employs prior to any work commencing. In particular, there is a difference between research based on a framework and that which is not. It has been argued that research that centres around a framework is more effective as it allows researchers to select appropriate questions to be answered and methods of collecting data.[275] Although there are numerous theoretical frameworks, suggested by some to number 13,[276] Bodner sought to categorise them into three main categories.[277] These categories are Hermeneutics, Critical Theory, and Constructivism and Social Constructivism (although others consider constructivism as a worldview).

Critical Theory is the overcoming of the uneven balance of power between groups of individuals and is closely related to feminism and Afrocentric views.[278]This area has been criticised for its lack of neutral perspective.[278] Constructivism or Social Constructivism as discussed previously centres around an individual's comprehension of their experiences and how they contextualise this understanding into learnt knowledge.[278] Constructivism further sub-divides into Symbolic Interactionism, Pedagogical Content Knowledge and Models and Modelling. Hermeneutics refers to the providing of a voice for those individuals in a group who cannot speak for themselves or are traditionally ignored.[278] Hermeneutics in turn can be subdivided into seven further categories; Phenomenology, Phenomenography, Action Research, Narratology, Ethnology and Ethnomethodology, Situated Cognition and Communities of Practice. There is one final category which fits into none of the afore-mentioned categories which is Grounded Theory. Although many of the frameworks are described as discrete entities, it is common to have multiple theoretical frameworks which underpin a researchers study. Grounded theory is used in this research and is discussed here.

1.4.2.1 Grounded Theory

Grounded theory is a systematic framework involving the development of theories based on analysis of data. Participants engage in a world that requires reflexive interaction as a result of goals being driven by behaviour relating to social interaction.[279] It is primarily used in the social sciences as a means of analysing qualitative data. It is perceived as the reverse framework from conventional scientific theory used in other frameworks, in that the hypothesis is derived from the words and actions collected rather than proving/disproving particular phenomena. In this research framework the method is divided into five stages. Firstly, the data is collected through a variety of sources (questionnaires, interviews etc.). Secondly, the data is analysed for emergent themes within the data sets without preconceptions of their importance. These thematic events are then ‘coded’, by which key points are extracted from the data and identified for their importance. Finally, a hypothesis or theory is developed centred around the data collected. It is believed that grounded theory develops theories that are more close to reality.[280] However, many researchers have hijacked the grounded theoretical framework in studies that are, lacking theoretical sensitivity engaging in purposive sampling and discrete sample interviews,[281] resulting in stigmatisation that grounded theory encourages an “anything goes” approach.[282] However, grounded theory is not unified and as a result four separate philosophical perspectives on what grounded theory is have emerged. These perspectives are the ‘original version’,[283] Glaserian grounded theory, Straussian grounded theory and constructivist grounded theory.[284, 285]

The original version of grounded theory soon diverged with the original authors separating their views in to Glaserian grounded theory and Straussian grounded theory. The main differences between these two perspectives emerge in the collection and analysis of the data. Glaserian grounded theory is believed to be a more true representation of the 'original version', especially with the approach to data analysis, whereas Straussian theory is considered reformative with respect to data collection.[281, 286, 287] The original text documenting the data analysis process was vague, and consequently, Strauss, in collaboration with Corbin, attempted to increase understanding of data analysis during the grounded theory process.[288, 289] However, this explanation of the data analysis process was criticised heavily by the more purest grounded theorists, prompting comments that the analysis process had become programmatic and overformulaic.[290] Furthermore, Glaser openly criticised his former research partner as promoting grounded theory as a "forced, full, conceptual description," further stating that Straussian theory was no longer grounded theory and should never be considered so.[281] These comments from Glaser prompted Strauss and Corbin to later modify their initial approach to data analysis and state that it had not been their intention to promote a rigid grounded theory and they were merely "guidelines, suggested techniques but not commandments."(pg 4)[289] Glaserian and Straussian grounded theory differed further on whether verification should be the product of grounded theory.[287, 291-293] Straussian grounded theorists believe that induction, deduction and verification are "essential", whereas the Glaserian grounded theorists maintain that grounded theory should be inductive only.[281] This is because in 1967 Glaser and Strauss wrote "… generation of theory through comparative analysis both subsumes and assumes verification and accurate description, but only to the extent that the latter are in the services of generation,"(pg 28)[283] inferring that the process is inductive and theory developing.[287] Straussian grounded theorists stress the importance of deduction and verification, suggesting the role induction plays in grounded theory as being over stated.[287, 294] Straussian and Corbin wrote that validation was "a process of comparing concepts and their relationships against data during the research act to determine how well they stand up to such scrutiny."(pg 24)[289] In this definition, the process of data analysis in grounded theory shifted for Straussian grounded theory, a claim never denied by Strauss, from an inductive process to an abductive process.[294] This transition means that Straussian grounded theory has moved towards a more constructivist perspective of grounded theory where the "researcher arrives at the most plausible interpretation of the observed data."(pg 603)[294] Still, Glaser insists that the only true version of grounded theory is the one originally proposed, insisting the theory emerges from the actual data.[291, 293-295]

Constructivist grounded theory was first proposed by Charmaz[284, 285] as an alternative to the complications associated with the Glaserian theory[281] and Straussian theory[289] as previously discussed. Charmaz stated that the objective of developing constructivist grounded theory was to "take a middle ground between postmodernism and positivism, and offers accessible method for taking qualitative research into 21st Century."(pg 250)[284] The addition of the constructivist perspective in the arsenal of a the grounded theorist's methodology maintained the inductive nature of the 'original version,' with the rise of philosophical stance of constructivism.[296] Furthermore, Charmaz criticises the reporting of findings in the 'original version.' Instead of the observation of patterns emerging from the data, Charmaz proposes that researcher and participant construct the common understanding of a shared reality and this shared reality is the objective of the researcher.[285] However, the same criticism about alteration of the original grounded theory methodology levelled towards Strauss have been directed at Charmaz. The main question has been, how far can an original methodology be altered or modernised before it no longer can be considered that original methodology .[297] Glaserian theorists contest that constructivist grounded theory differs too much from the ‘original version’ to be considered grounded theory.[294]

A review released by Taber attempts to provide a formal structure to the grounded theory approach, and Figure 10 shows the flow chart algorithm used to help chemistry education researchers enter the field of grounded theory research.[298] As with the initial five stage process, Taber’s model begins with the collection of data and development of the codes, demonstrating the cyclic nature of grounded theory. However, the algorithm does run the risk of falling into the trap of becoming too prescriptive, the same trap Glaser accused Strauss of falling into with the development of Straussian Theory. It is clear that the model does allow chemical education researchers access to an unfamiliar research methodology they may struggle to understand, although care should be taken to ensure the prescriptive nature of the flow chart does not impede the continual development of exploring the data under a grounded theory methodology.

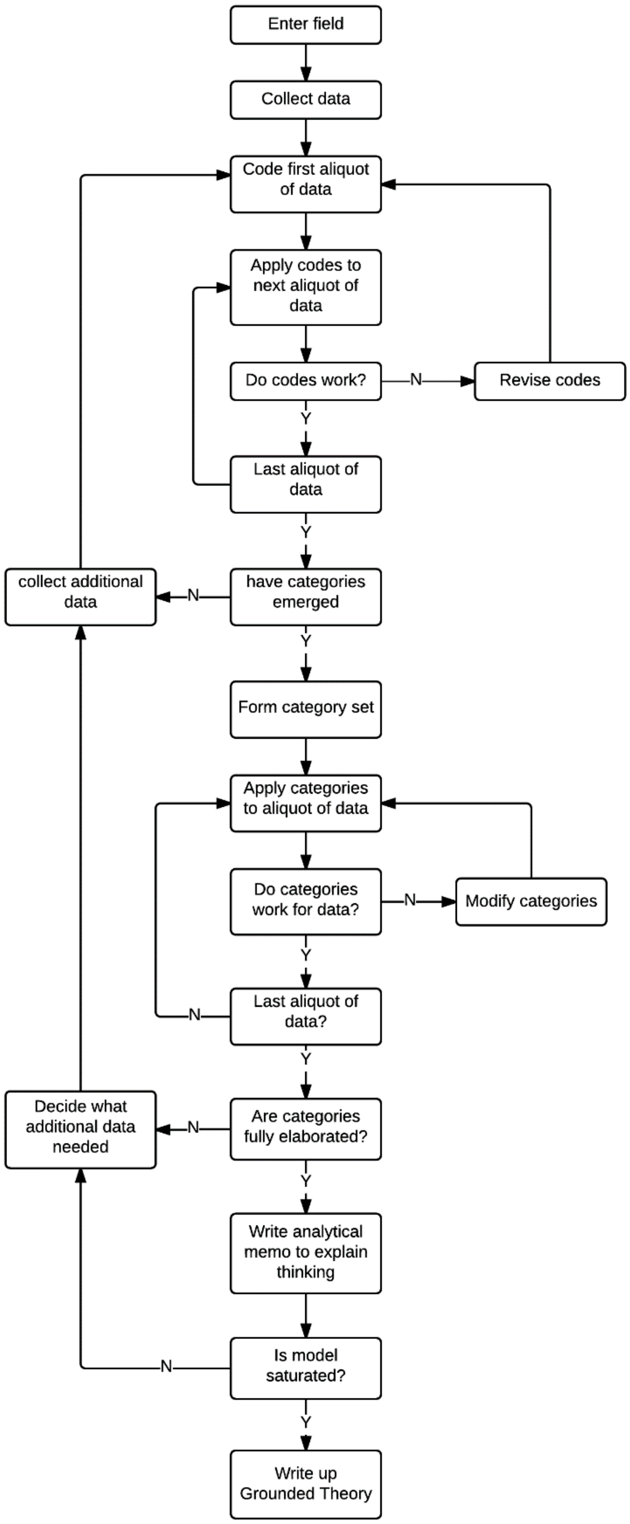

Figure 10 A schematic showing the nature of Grounded Theory.[298]

1.5 Aims of the Project

This chapter has demonstrated the importance of understanding both student limitations with solving problems and the importance of cognitive functionality of students when engaged in problem solving activities. It has also reported that employers view problem solving as a desirable skill in graduates. However, they often complain that graduates are ill-equipped in problem solving for the working environment. The ability of students to engage in successful problem solving has been linked to cognitive structure and styles, although the impact of these cognitive components upon open-ended problem solving is not clearly understood, especially the approaches used by students. There is limited understanding of the approaches used by students in different science disciplines when solving open-ended problems. Therefore the objectives of this research project are:

- To understand, through qualitative research, the approaches used by science undergraduate students when solving open-ended problems.
- To understand, through qualitative research, the differences and similarities between expert and novice problem solvers.
- To investigate emerging patterns between different cognitive functions, such as M-capacity (FIT) and field dependence (GEFT), and whether there are any patterns between cognitive function and approaches used when solving open-ended problems.
- To understand the implications of different approaches used by science discipline undergraduates and their impact on teaching and learning.

2 Qualitative Methodology

This chapter will provide a detailed description of how a grounded theory approach was used to investigate the different approaches used by undergraduates from various science disciplines when solving open-ended problems.[281, 285, 299] This chapter will also discuss the process used to evaluate the quality of participant solutions.

2.1 Open-ended Problems

As part of the experimental design, suitable open-ended problems had to be identified to challenge the students. The questions met the parameters of Johnstone's type 8 problems.[85] Type 8 problems are questions where the data given is incomplete, the methods for tackling the problem are unfamiliar and there is no single correct answer[85]. Such problems are defined as open-ended problems in this study.

The first problem presented to the participants was one that required them to use no scientific knowledge and was intended as an ice breaker to get them used to the style of think aloud protocols and the open-ended problems. The question chosen as the ice breaker was the same for all disciplines. The question was, "how many toilets do you need at a music festival?" Participants were not given any of the data that would be required to answer the question. The method of reaching a solution was believed to be unfamiliar to all participants and there was no single correct solution. In addition to the non-scientific question, discipline specific questions were developed in consultation with academic staff from the appropriate discipline. For participants from chemistry, physics, academic, industrialist, postgraduate and interdisciplinary science discipline groups the following questions were used:

1) How far does a car travel before a one-atom layer is worn off the tyres?
2) What is the mass of the Earth's atmosphere?

The questions that were developed for participants in sports rehabilitation and pharmacy groups were:

1) How much salt is lost through sweat during a 90 minute football match?
2) How much carbon dioxide is produced during a marathon?

Academic staff in psychology agreed that the following questions should be used for participants in psychology:

1) How many units of alcohol would it take to effect the episodic memory of everyone in the night club on a Saturday night?
2) How many children in the UK have received a certificate of special educational needs for ADHD?

It was determined that each of these questions could be answered in a numerical way or using a descriptive answer which meant individuals were not forced to make calculations if they felt they didn't need to.

Five chemistry participants were interviewed with an alternative question order, to determine whether the question order influenced the approaches used by the participants.. The new order for these five participants were:

1) How far does a car travel before a one-atom layer is worn off the tyres?

2) How many toilets do you need at a music festival?

3) What is the mass of the Earth's atmosphere?

Apart from the question order, all other conditions for these five participants were identical to those for other participants who completed the questions in the 'conventional' order.

In addition to the question order variable, five participants from physics were given a different set of open-ended problems to identify whether different approaches and profiles emerged from different open-ended questions. The alternative questions used were:

1. Usain Bolt is hailed as the world's fastest man. How much kinetic energy does he have as he crosses a finish line in a 100m race.
2. The Large hadron Collider uses 96 t of superfluid He4 to maintain the operating temperature of 1.9 K. How long would that amount of He keep the world supplied with party balloons?
3. If all passengers went to the toilet before a flight, how much fuel would be saved on a flight between Heathrow and Chicago?

Once again all other conditions were identical to those participants who completed the original questions. The participants used in this research are identified in Table 7.

Table 7 Complete list of participants from different science disciplines used during this research

Academic Institution- Discipline	Number of Participants
University of Hull- Chemistry	12
University of Strathclyde- Chemistry	5
University of Hull- Physics	10
University of Edinburgh- Physics	7
University of Hull- Sports Rehabilitation	6
University of Hull- Psychology	9
University of Hull- Experts	5
University of Leeds- Experts	1
University of East Anglia- Experts	3
Industrial Experts	6
University of Leicester- Interdisciplinary Science	7
Monash University- Pharmacy	14
University of Hull Postgraduate Students- Chemistry	5
Chemistry Expert Groups	3
Physics Expert Groups	2
Chemistry/Physics Mixed Expert Groups	2
2nd Year Undergraduate Chemist Groups	2
1st Year Undergraduate Chemist Groups	1
Total	100

Undergraduate participants recruited from science disciplines were studying a full time undergraduate degree course in their chosen discipline at the time of participation. All undergraduate participants were studying at level 4 education (first year of undergraduate study in England and Australia, and second year of undergraduate study in Scotland). These students were self-selecting following an open invitation for participants under the previously defined parameters. Self-selecting means that all participants who identified a wish to participate were allowed to do so. Participants studying Interdisciplinary

Science were specifically recruited because the course they were studying was delivered solely using a problem-based learning (PBL) approach.

Postgraduate participants were recruited from the chemistry department at the University of Hull. All participants in the postgraduate group had obtained a masters level qualification and were studying towards a doctorate in chemistry. The postgraduate participants were self-selecting.

Academic participants were drawn from chemistry academic staff at UK Higher Education institutions with at least eight years of academic experience. Industrial participants were currently working in the chemical sector in the UK and held a degree in chemistry. The industrial participants had been working in the chemical sector for more than five years.

2.2 Ethical Approval

All research that is conducted using human participants requires ethical approval before commencement. Ethical considerations for a researcher using human participants must include:

- Moral codes of practice,
- Considerations about what information is being collected
- Signed informed consent from the participant.
- Identification and reduction of risks towards participants
- Confidentiality and Data Protection issues
- Financial incentives and benefits received by participants
- The right of participants to withdraw from the study at any time without providing reason, and any data acquired from withdrawing participants are destroyed.

The University of Hull's ethical guidelines were followed and where possible identified risks to participants were removed. Ethical approval was obtained for all tests, questions and data collection methods by the Departmental Ethics Committee.

All participants were provided with written information about the study and ethical guidelines and considerations involved with the research study. They were informed that all digital information would be kept on university servers and that all paper data would be stored in a locked office. Any quotes that were used as part of a thesis or publications would be anonymous with participants being assigned a code. The individual who would be represented by the code would only be identifiable by the research team, and gender specifics which could be used to identify participants would be removed from the study. Each participant was given the opportunity to withdraw from the study at any time until a time where their data had been used in a thesis or publication. At this point it may be unfeasible to remove their data from the study. Participants were informed of these details at the time of acquiring informed consent. The full completed ethical approval form from the University of Hull for human participants can be seen in the appendix 1. Most other university institutions involved in this study accepted ethical approval from the University of Hull, however the University of Leicester required their own ethical approval form for gathering data from their student participants. The ethical approval form from the University of Leicester can be seen in appendix 2.

2.3 The Think Aloud Sessions

Use of think aloud interviews during this study allowed the investigator to observe approaches that participants used when they encountered open-ended problems.[85] Think aloud protocols allowed the researchers to gain insight into the process of solving problems rather than just analysing the final solution. Think aloud protocols are sometimes called concurrent verbalisation. Although based around the introspective approach in which the individual self-evaluates their understanding, there is greater focus placed on cognitive processing using the think aloud protocol rather than just analysing an individual's solution. When conducted correctly the think aloud data collection method does not impede either cognitive processes or self-evaluation. However, the method is incapable of identifying unconscious processes. It should also be stated that, due to the high cognitive load brought about through verbalisation, researchers are only provided with a glimpse of the cognitive processing rather than a "complete account."[300] Researchers utilise these verbal reports for their rich data mining, exploring topics such as decision making,[301] linguistic development[302] and literary comprehension.[303] With established protocols the think aloud interviews can be used to reveal in-depth data about problem solving approaches. Participants are encouraged to vocalise thought processes whilst solving complex problems. As Smagorinsky states, verbalisation of thought is a "process through which thinking reaches a new level of articulation."[304]

Think aloud protocols[305] can allow investigators to analyse the progression of thought processes as the participants engage with the activity and analysed through qualitative coding. Codes are a shorthand representation identifying characteristics and themes embedded within the transcripts, recordings or written data used in qualitative data collection methods. Using emergent themes and timeline analysis based on the think aloud interviews, researchers are able to establish if characteristics present in certain participants have significant impact upon a successful strategy.

At the start of each problem solving session the participants were informed of the intentions of the exercise and the following guidelines issued to each participant individually.

- There is no single correct method to solve these problems.
- There is no single correct answer.
- Include every piece of information that you think may help you with answering these problems.
- Not all the information has been provided. However, you may ask me for specific pieces of information. If I have it on my pre-assigned information sheet I will give you that information.
- Just because I don't have a particular piece of information it doesn't mean to say your strategy is incorrect.
- You may use a calculator to aid you. However, you may not use a smart phone or a device that can access the internet.
- Participants have 20 minutes to answer each question.
- At the end of each question I will ask "are you happy with that answer." That is not me questioning your answer, just me confirming for the recording that you are happy to continue.

Each participant was provided with the opportunity to ask further questions before the interview commenced to ensure that they understood the task required of them. With the explanation of the procedures complete, the students then began to answer the questions.

The first question was identified to the participant as a warm up question with a real world context and limited to no scientific content. The researcher read the question to the participant, and the participant was able to read a paper copy of the question. Participants then answered the question whilst articulating their thoughts, asking for information that they required. The participant was allowed to answer the question sufficiently to their satisfaction or until 20 minutes had elapsed, which ever was sooner. Having completed question 1 the participant was asked to proceed to question 2. The question was read out by the researcher and the participant allowed to read a paper copy of the question. The participant then proceeded to answer question 2, asking for information that they required. After the participant identified they had answered the question sufficiently or 20 minutes had elapsed they were asked to move onto question 3.

The data was collected using a Live Scribe device. A live scribe smart pen is an electronic ball point pen that incorporates a microphone and camera. When used with Anoto digital paper it records what is written by participants for analysis with computer software, synchronising those notes with the audio recording. This allows the researcher to replay particular portions of written data and listen to what is being said at the same time. This data can then be uploaded to Livescribe desktop software for more in-depth analysis. The particular model of Livescribe pen used in this study was the Echo® smartpen. Data is easily and securely transferred between researchers through the desktop software. The pen is encrypted for access by only one individual’s login details. Failure to provide the correct access details results in the pens data being wiped clean.

During the interview process the researcher used prompt phrases such as “What are you thinking right now?” and “Could you explain to me what you have just done?” These prompts were used during prolonged periods of silence by the participant in an attempt to reengage the think aloud protocol. Throughout the problem solving session the researcher sat opposite the participant to encourage a dialogue between them and allowing encouragement. Where possible, noise was reduced, not only to ensure a good recording, but also to allow the participant to feel comfortable vocalising their thoughts without the feeling they may be overheard by others.

2.4 Code Development Study with Chemistry and Physics Undergraduate Students

The study developed codes by processing data through an adapted Bryman's four stages of qualitative analysis, identifying themes that emerged from the data. A code is a single word or short phrase that "symbolically assigns a summative, salient, essence-capturing and/or evocative attribute for a portion of language or visual data."[306] Coding is the 'critical link' between the data collected and their intended meaning.[307]

Level 4 undergraduate student participants in chemistry and physics were invited to participate in answering three specific open-ended problems for chemistry and physics students as identified in section 2.1 using a think aloud protocol. Table 8 shows the number of participants used to acquire these codes.

Table 8 Number of participants from chemistry and physics used to develop the codes

University and Subject	Number of Participants
University of Hull, Chemistry	12
University of Hull, Physics	5
University of Edinburgh, Physics	7
Total	24

Each participant's Livescribe pencasts were transcribed to ensure that no details were overlooked. The key focus of this stage of the research was the approaches employed by the participants whilst answering each question rather than the quality of the solution. The data was analysed through a grounded theory approach to establish what themes emerged from the data. Using a grounded theory approach the data was analysed through a four step process modelled around Bryman's 4 stages of qualitative analysis:[308]

1) The data and audio recordings were read and listened to and notes taken about the overall strategy employed by the participants. The transcripts and audio files were analysed to decide if there were any initial themes emerging, e.g. little evaluation, becomes confused etc. These emergent themes were written down.
2) Having reviewed the data for the first time, the text and audio files were studied again in greater detail to establish if any themes were hidden, which the initial stage had failed to identify. Key words were highlighted which supported these emerging themes.
3) The next stage was to review and eliminate the themes that had been repeated and similar themes combined. This process of collapsing similar codes is called a redundancy approach this is because two similar codes are 'redundant'
4) The final list of themes were then given a shorthand code to represent the presence of a theme ready for the subsequent coding processes.

Using this approach the theories emerge from the data collected rather than using the data to test a hypothesis.

2.4.1 Inter-Rater Reliability

The method of inter-coding is used in qualitative research to ensure that there is agreement over interpretation of the raw data. It is also used to establish whether the definitions of the emergent themes are sufficiently robust to identify their intended characteristic. The emergent themes and associated codes were shared with colleagues at University of Edinburgh. Four coders took the same two randomly selected transcripts and coded them using the definitions of the emergent themes as described in section 2.4. The transcripts that were coded were one participant from chemistry and one participant from physics. No coder knew which participant was a chemist and which was a physicist. The coders listened to each live scribe pencast and audio transcript multiple times, coding the transcript each time. When a theme was observed the coder wrote the code corresponding to the identified theme next to its location in the transcript. The coding process was completed independently of each other to ensure no collusion. This data was then collected to establish whether themes in the transcripts related to the codes they were assigned. A percentage agreement was given for each code, for each participant and for each question. Once the percentage agreement had been determined the coders met to discuss areas where disagreement with a coded theme occurred to refine the definitions for the themes.

2.5 Coding Pencasts and Transcripts for Individual Participants

Once the individual themes had been established and validated using inter-rating reliability approach, individual participant approaches were coded. The audio transcripts from participants were analysed using the codes, developing a profile of approaches for each individual. Each audio recording was transcribed long hand to ensure that no details were over looked. One researcher then coded each transcript whilst listening to the audio recording. When the researcher encountered a theme they wrote the corresponding code next to it on the transcript. The researcher read through each transcript multiple times whilst listening to the pencast recording to ensure that no themes were missed. Each code was quantified for the number of occurrences observed. These resultant individual profiles were then combined to develop a discipline profile of approaches to ascertain how discipline cohorts approach open-ended problems.

2.6 Group Studies

A separate component of this study was investigation of how strategy development and approaches to solving open-ended problems occur within a group context. Groups of students and experts were created from the physical sciences. See Table 7 for a list of groups for this section of the study.

The participants answered the same questions described in section 2.1 Their pencasts were transcribed and subsequently coded using the same codes as identified in section 2.4. The outputs from each group were treated as one individual data set, despite having multiple members.

2.7 Primary and Secondary Cluster Analysis

Cluster analysis was carried out on the overall approaches for the overall profiles for all disciplines. A primary code is a cluster of codes that are the most prominent to the group, and a secondary code is a cluster of codes that hold secondary prominence. Prominence is determined through groupings of codes that cluster together based on percentage distribution of approach. For example, a cluster towards the top end of their distribution, normally within 50%

of the most prominent code (although not strictly set towards percentiles), would be considered the primary cluster and therefore the set of primary codes. The next cluster of codes after the primary group would be considered the secondary codes, as they represent approaches used by the group, but they are not the most prominent approaches. The use of the secondary codes was required to tease out the emerging subtle differences between the different emerging discipline profiles. Further clusters could be obtained, however, no further clusters were required further than secondary clusters to determine discipline differences.

2.8 Evaluation of the quality of solutions using 'Traffic Lighting' labels

Each solution from all participants in Table 7 were assigned a traffic light label based on the quality of their solutions alone without listening to their think aloud recordings. Each solution was evaluated for the quality of the answer and strategy. The following the traffic light labels which were used for all answers in this study were defined as:

- Red for a poor answer (a poor answer is one that is unrealistic e.g. 50,000 toilets for a music festival with 150,000 people) with little to no demonstration of a strategy.
- Amber for a good strategy demonstrated but a poor answer or for a good answer but no specific strategy demonstrated in their script.
- Green for a good strategy demonstrated with a good answer.

Each of the traffic lighted solutions were analysed to determine whether common themes emerged for each traffic light colour. The pencast recordings for each solution which was identified as red were analysed through the following 4 stage process:

1) The audio recordings were analysed to decide if there were any initial themes emerging, e.g. little evaluation, becomes confused etc. These emergent themes were written down.
2) Having reviewed the data for the first time, the audio files were studied again in greater detail to establish if any themes were hidden, which the initial stage had failed to identify.
3) The next stage was to review and eliminate themes that had been repeated and similar themes combined. This process of collapsing similar codes is called a redundancy approach and was because coding for similar approaches using two separate codes is ‘redundant’
4) The final list of themes were assigned that showed the most commonality amongst all red solutions. This means that the list of themes were not present in all red solutions but were common to a majority of solutions.

The four stage process was repeated for all the amber and green solutions.

2.9 Timeline Analysis

The different approaches used by each participant in Table 7 identified in the coding process were assessed for where each one emerged in the timeline of each solution per participant. Each solution was analysed by listening to the pencast recordings and viewing the solution time-lapse through the LiveScribe Desktop software. When each approach emerged the appropriate code was written down to give a chronological order of approaches. Phases of approaches were identified. A phase is defined as when multiple occurrences of the same approach emerged without interruption by other approaches. Each sequence of approaches was tabulated and colour coded to identify whether patterns of sequences were emerging depending on success or discipline.

3 Quantitative Methodology

The aim of this part of the study was to assess whether cognitive factors influenced how students solved open-ended problems. The cognitive factors were assessed using a bank of psychometric tests which created both an individual and discipline profile of cognitive function. The cognitive functions which were assessed were M-capacity (using the FIT) and field independence (using the GEFT). Participants in chemistry and physics were used to provide large data sets for the psychometric tests. Some participants that contributed to the qualitative study also provide data for the psychometric tests. The individuals who participated in both the quantitative and qualitative study had both components compared to determine if there is any correlation between the individual components.

3.1 Figural Intersection Test

As previously discussed in section 1.2.1 mental capacity can easily become overloaded when situations require the individual to exceed the upper limit of their M-capacity space when tasks require greater processing than the individual can handle (M-capacity).[309, 310]

During the psychometric study, participants completed the figural intersection task. The FIT is a paper and pencil administered test that can be used on both children and adults, and was designed by Pascual-Leone in 1967.

The tests were designed to assess Pascual-Leone's Theory of Constructive Operators.[111]

The FIT test was designed to exhibit good reliability and has been used as a research instrument extensively. The test has gone through many derivations and modifications achieving ultimately a fast, reliable and easy administrable test for the assessment of mental capacity. The test used throughout this research was a derivation of test FIT 8303[97] and will be referred to henceforth as FIT 8303 PS. Although intended to assess an individual's M-capacity, it has been used in other studies at a group level for three different purposes 1) to select a group of participants with an M-capacity suitable for their given age, 2) to provide a measure of M-capacity to be used in correlation studies and factor analysis and 3) to validate the M-operator construct through comparison of group performances and variable ages.[97] The focus of this research was towards a correlation study with additional psychometric tests associated with problem solving and field independence.

The FIT 8303 PS used for this research comprised of 31 test-items. The figural intersection task presented participants with two sets of simple geometric shapes. The set on the right side of the page was called the presentation set and the set on the left was called the test set (Figure 12). The test set contains all the shapes presented in the presentation set, although they are arranged in an overlapping configuration. Within this overlapping configuration lay a single area of intersection which was simultaneously residing in all the shapes. This was called the common area.

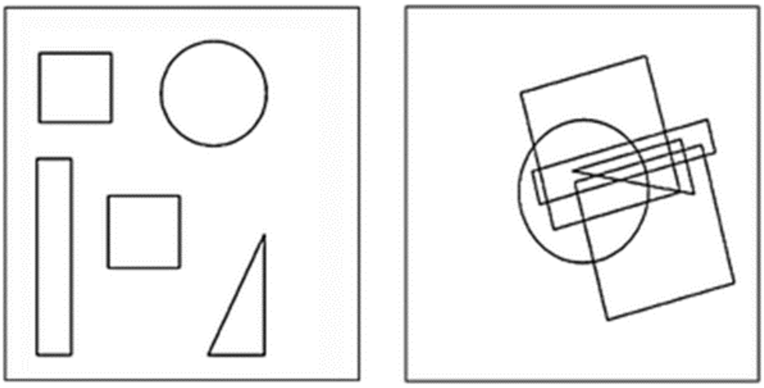

Figure 11 Example of an item from the figural intersection test (FIT)

Participants were then required to identify the common area, shading in the appropriate area. The shapes in the tests set could differ in size and orientation from those in the presentation set; however, they did match the participation set in shape and proportion. In some of the test sets there are additional or irrelevant shapes which do not have a common intersection with the other test shapes. These irrelevant shapes were not found in the presentation set and should be ignored as distracters. Some research suggested that the irrelevant shapes contribute to the M-demand of the problem, and may increase the difficulty of the test item by one unit despite the irrelevant shape not contributing to the common area.[311-314] The number of shapes in the presentation set varied between 2 and 9, with the participant achieving an M-capacity score with a correct answer equal to number of shapes present in the presentation set.

3.1.1 Administering the FIT 8303 PS test

Each participant was presented with a booklet and coloured pen (preferably a red or green pen to ease the marking process). The booklet comprised of pages where the paper is thick enough so that the shapes do not show through from the next page. 70 g m^{-3} appears to sufficiently prevent this. Should the lines show through the paper from the next page, participants can be presented with a blank piece of paper to slide between sheets to mitigate this affect.

The instructions for administration are taken from the Manual for FIT: Figural Intersection Test.[97] The instructions are aimed at children but can easily be adapted and simplified for adults. Each of the eight instructions helps participants understand the different concepts they will encounter whilst completing the test and ensures participants understand what to do when participants encounter such a concept.

The testing process was conducted both during individual interviews and in large classes. The original manual states that there is no time limit. However, during this research a time limit was included for pragmatic reasons. Excluding the explanation stages of how to complete the test, participants were allocated 20 minutes to complete as many questions as possible.

Errors that could be encountered during the testing period include:

1) Multiple marks within the test set shapes. This may include an individual outlining the test shapes as they locate them, or lightly placing their pen in the location, leaving multiple marks. Some participants will try and correct their answer resulting in multiple dots appearing on the page. Additionally some individuals forget the instructions too and place lots of dots multiple times in the test set shapes.
2) Some participants may place dots on the lines of the test shapes, or large dots that cover multiple areas.
3) Missed items. Subjects should attempt as many items as possible even if they have to guess. Should the participant complete the test

before the allotted time has elapsed they should be asked to check for incomplete tasks.

Where each of these errors were observed a no score should be marked on the individual's sheet. This is because each of these errors either impact on the difficulty of the test item, or demonstrate an uncompleted test item and the test item is considered failed.

Each item in the participant's booklet was assessed for a pass or fail; with an overall test score calculated. An item is considered passed if there was a mark within the area of common intersection, where the mark does not exceed the area of the common intersection. There should have been no other mark on the test set. Marks occurring in the presentation set of shapes were not considered when marking the score. A failure for a task was also awarded if there were no marks on the test area or multiple marks are shown on the test shapes, as stated previously in the possible identified errors. The scores were assessed through three different methods. However, the most appropriate results were observed with the FIT-1, and as such this was adopted for the rest of the study. FIT-1 score looks simply at the total number of items passed under the assumption that if a participant passes a high proportion of items belonging to a class then they tend to pass all items belonging to a lower class.[98, 102] It is deemed a conservative valid score than other methods of scoring the FIT.

The number of participants that completed the FIT test are shown in Table 9.

Table 9 Number of participants per discipline that completed the FIT test

Discipline	Number of Participants
Chemistry	108
Physics	66
Sports Rehabilitation	5
Psychology	9
Interdisciplinary Science	8
Academic Experts	9
Postgraduate Students	5
Total	210

3.2 Group Embedded Figures Test

The Group Embedded Figures Test can be used to assess an individual's ability to process mass information or stimuli with a view to making sense of complex situations. At times more information is presented than is required to understand the task and this provides a disruptive effect. The ability to select the most important pieces of information is referred to as the learner's field dependence / field independence, or dis-embedding ability.

Participants were assessed using a Group Embedded Figures Test (GEFT) (Figure 13 [315]) where participants are required to recognise a simple shape amongst a more complex pattern, thus restructuring information for correlation.[116]

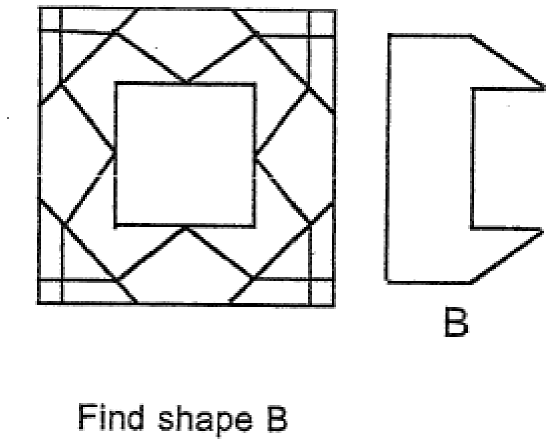

Figure 12 A sample item representatives of the problems in the Group Embedded Figures Test.[315]

The more shapes correctly identified by the participant, the more field independent the individual is considered to be.

The GEFT is only capable at assessing the individual's field-independence and is incapable of assessing an individual's field-dependence as previously stated in section 1.2.2.

3.2.1 Administering the GEFT Test

The test booklets and coloured pens were distributed to the participants and participants were asked to complete identifying information on the front of the booklet. Participants were then shown an example question for the test and what was required of them using Figure 14.

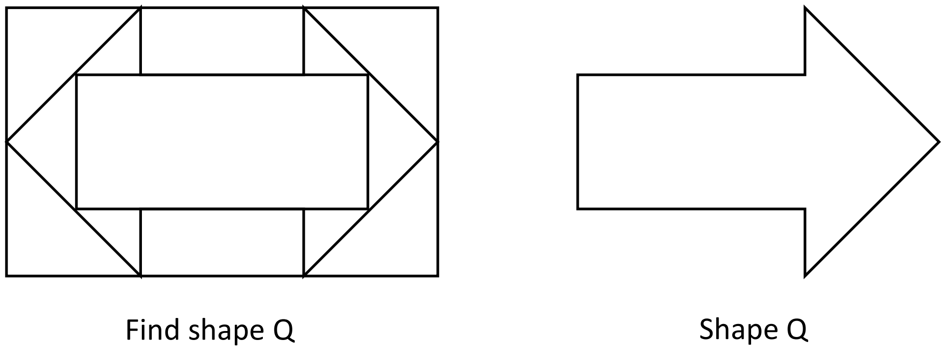

Figure 13 GEFT example shown to participants prior to completing the GEFT booklet

Participants were then asked whether they understood the task that was being asked of them. Following verification that participants understood the task they were told additional rules that applied. These rules were:

- There is only one correct answer although some images may look similar. The shapes appear in the test item in exactly the same size and orientation as they appear at the back of the booklet. The shape cannot be rotated or mirrored.
- The shape list must remain at the back of the booklet and cannot be removed. Nor can the participant slant their booklet revealing both the question matrix and the shape list.
- The participant may make one alteration to their answer. If alteration is required the participant must draw an arrow indicating the wrong answer marking the arrow with a cross, and draw an additional arrow for the correct answer marking the arrow with a tick.
- The participants had 20 minutes to answer as many test items as possible, you are not expected to finish the entire test booklet.

- If the participant becomes stuck with an individual test item, they were allowed to leave that item until the end and move onto the next test item.

The GEFT was scored by totalling the total number of correct items out of a possible 20 test items. Where the participant got the answer correct for a test item they were given a score of 1 for that item. Where a participant provided an incorrect answer for a test item the individual will be given a score of 0 for that item. An item is considered to be incorrect if:

- The participant identifies the wrong area for their answer on a test item, this would include a participant identifying the correct shape but adding additional areas to the shape area or shading the mirror image as seen in Figure 15.
- The participant identifies the incorrect shape in the test item, for example identifying shape B instead of shape D.
- The participant makes more than one correction to an individual test item.

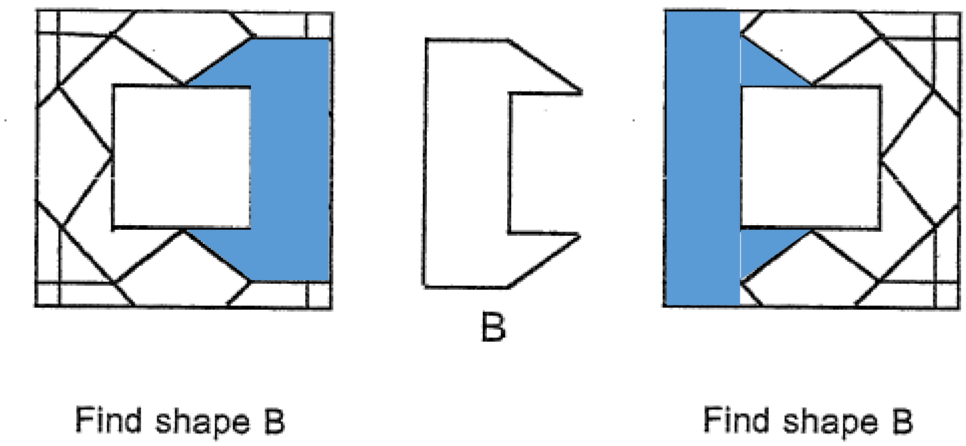

Figure 14 Example of two incorrect answers for the GEFT test. The left image shows the correct shape however it has been rotated through 180°. The right side image the incorrect shape has been shaded because the individual has shaded a too large an area

The number of participants that completed the GEFT test is shown in Table 10.

Table 10 Number of participants per discipline that completed the GEFT test

Discipline	**Number of Participants**
Chemistry	71
Physics	75
Sports Rehabilitation	5
Psychology	9
Interdisciplinary Science	8
Academic Experts	9
Postgraduate Students	5
Total	182

4 Qualitative Results

This chapter focuses on the results of the qualitative study. The chapter will discuss the following results:

1) Analyses of data using a grounded theory approach to identify key themes and characteristics used whilst solving complex problems.
2) Measuring inter-rater reliability of using four separate coders
3) Coding responses from individual participants to create an individual profile
4) Generating a discipline profile from participants' responses
5) Traffic lighting individual solutions for their quality and determined whether patterns in approaches related to success.

The participants were each given a unique identifier. These identifiers were generated as follows:

Type of Participant:	U= Undergraduate Student	EX= Post Undergraduate
Institution Code:	HULL = University of Hull	STRA = University of Strathclyde
	EDIN = University of Edinburgh	LEIC = University of Leicester
Discipline Code:	CH = Chemistry	PH = Physics
	SR = Sports Rehabilitation	PS = Psychology
	ISCI = Interdisciplinary Science	PG = Chemistry Postgraduate
	ST = Chemistry Academic and Industrialists	
Participant Number:	X = a number	

For example, UHULLCH1 is an undergraduate chemist at the University of Hull, and they are the first participant from that group.

4.1 Developing the Codes Using Responses of Physics and Chemistry Undergraduate Students

The transcripts and pencasts of level 4 physics undergraduates at the University of Edinburgh and chemistry undergraduates the University of Hull were analysed using Brymans 4 stages of qualitative analysis for emerging themes using a grounded approach (*N=13*). The initial emerging themes are shown in Table 11:

Table 11 Initial emerging themes using Brymans 4 stages of qualitative analysis using a grounded theory approach

Confusion	Evaluation	Guessing	Identifies strategy
Making calculations	What is being asked?	Using approximations	Reluctance to commit
Incorrect identification of information	Distracted by details	Confused by terminology	Using personal experience
Making estimations	Identifying what information is needed?	Stepwise strategy development	Missing evaluation
Confidence	Unit conversion	Creating a model	Flaws
Reasoning	Using algorithms	Using equations	

Some initial themes had very similar characteristics, such as making approximations and making estimations. Such themes were then collapsed together to remove redundancy within the theme pool.

The final list comprised of nine themes with an associated definition to enable the coder to correctly annotate and identify the characteristics. Each theme was given a corresponding three letter code. There was a + and –

version of each code. The + and - do not denote value judgements or absence but describe characteristics. The codes developed were:

Identifying information needed- The participant identifies information that they believe is important for completing the task whether it's correct or erroneous information.

IIN+ The participant identified a specific piece of information they think they need.

IIN- The participant fails to identify a specific piece of information they need.

Approximations and Estimations- The participant makes approximations of values to ease calculations and estimates required numerical values.

A&E+ The participant makes realistic estimations of numerical values, approximations are made to ease calculations.

A&E- The participant fails to make realistic estimations, or is unable to estimate required values, fails to make approximations to ease calculations.

Algorithmic- The participant uses numerical values or equations to formulate their strategy and solve the problem

ALG+ The participant uses calculations and/or equations to solve the problem.

ALG- The participant does not use calculations and/or equations to solve the problem.

Evaluation- The participant evaluates each stage of their strategy and their final answer.

EVA+ The participant evaluates their strategy and/or their final answer.

EVA- the participant does not evaluate either the strategy or answer.

Identifying the problem and framing- The participant clarifies what the problem is asking before developing a strategy.

IPF+ The participant reflects on what is being asked in the problem.

IPF- The participant does not reflect on the problem creating uncertainty in how to proceed.

Developing a Strategy- The participant develops a clear strategy in order to tackle the problem.

DAS+ The participant develops a clear strategy.

DAS- The participant does not develop a clear strategy.

Not distracted by details- The participant does not become distracted by the detailed context of the question

NDIS+ The participant does not become distracted by context or lack of information.

NDIS- The student becomes distracted by context and lack of information.

Confidence and No Confusion- The participant is confident about tackling the problem, what strategy to employ and the data required

CC+ The participant is confident.

CCP- The participant becomes confused with how to tackle the problem.

CCA- The participant lacks confidence in their abilities and knowledge.

Logical and Scientific Approach- The strategy employed by the participant involves logical progression, with reasoning. Scientific knowledge is used to establish their strategy.

LSA+ The participant employs a logically progressive strategy and/or grounded in scientific reasoning.

LSA- The participant employs an illogical strategy, with little grounding in scientific reasoning.

These codes were used for subsequent coding of individual participants.

4.2 Inter Rater Coding

The inter-rater coding was conducted by four coders on the transcripts of two undergraduate participants, one who was a physicist and another who was a chemist. Each of the two participants had answered three questions. The four coders analysed the two transcripts independently from each other so there was no collaboration. Coders used the codes identified in section 2.4 and assigned the appropriate code when they observed the described characteristic. At the time of coding none of the coders knew to which discipline the participants belonged. The two participants were identified solely as participant A and participant B. Once the coders had completed their analysis they gathered together to discuss their findings and allocations of the codes. Table 12 and Table 13 show the coder allocation for the codes for each participant per problem giving a percentage agreement per code, per problem and overall agreement:

Table 12 Results of themes observed in participant A as assigned by four coders

Participant A Q1				
Coder1	Coder2	Coder3	Coder4	Agreement %
INN+	INN+		INN+	100
A&E+	A&E-	A&E+	A&E+	75
ALG+	ALG+		ALG+	100
EVA-	EVA-	EVA-	EVA-	100
IPF-	IPF-		IPF-	100
DAS-	DAS-		DAS-	100
NDIS+	NDIS+		NDIS+	100
CCP-/ CCA-	CCP-/ CCA-		CCP-/ CCA-	100
LSA-	LSA-		LSA-	100
			Overall for Q	97
Participant A Q2				
INN+	INN+		INN+	100
A&E+	A&E-	A&E+	A&E+	75
ALG+	ALG-		ALG+	66
EVA+	EVA+	EVA+	EVA+	100
IPF-	IPF-	IPF+	IPF-	75
DAS-	DAS+	DAS+	DAS+	75
NDIS+	NDIS+		NDIS+	100
CCP-/ CCA-	CCP-/ CCA-		CCP-/ CCA-	100
LSA-	LSA-		LSA+	66
			Overall for Q	81
Participant A Q3				
INN+	INN+		INN+	100
A&E-	A&E+		A&E+	66
ALG+	ALG+	ALG+	ALG+	100
EVA+	EVA-	EVA-	EVA-	75
IPF+	IPF-		IPF-	66
DAS+	DAS-		DAS-	66
NDIS+	NDIS+	NDIS-	NDIS+	75
CCP-/ CCA-	CCP-/ CCA-		CCP-/ CCA-	100
LSA-	LSA-	LSA+	LSA+	50
			Overall for Q	77.41
			Overall Total	85

Table 13 Results of themes observed in participant B as assigned by four coders

Participant B Q1				
Coder1	Coder2	Coder3	Coder4	Agreement %
INN+	INN+		INN+	100
A&E+	A&E+	A&E+	A&E+	100
ALG-	ALG-		ALG-	100
EVA-	EVA+		EVA+	66
IPF+	IPF-		IPF-	66
DAS-	DAS-		DAS-	100
NDIS+	NDIS+		NDIS+	100
CC+	CC+		CCP-/ CCA-	66
LSA-	LSA-	LSA+	LSA+	50
			Overall for Q	83
Participant B Q2				
INN+	INN+		INN+	100
A&E-	A&E+	A&E+	A&E+	75
ALG+	ALG-		ALG+	66
EVA-	EVA+	EVA-	EVA+	50
IPF+	IPF+		IPF+	100
DAS+	DAS+		DAS+	100
NDIS+	NDIS+		NDIS+	100
CCP-/ CCA-	CCP-/ CCA-		CCP-/ CCA-	100
LSA+	LSA+	LSA+	LSA+	100
			Overall for Q	87
Participant B Q3				
INN+	INN+		INN+	100
A&E-	A&E+		A&E+	66
ALG+	ALG-		ALG+	66
EVA-	EVA-	EVA-	EVA-	100
IPF+	IPF+		IPF+	100
DAS+	DAS+		DAS+	100
NDIS-	NDIS+		NDIS+	66
CC+	CC+	CC+	CCP-/ CCA-	75
LSA+	LSA+	LSA+	LSA+	100
			Overall for Q	87
			Overall total	85

Using Table 12 and Table 13 the coders identified where they agreed and disagreed with the assignment of codes. Table 12 and Table 13 shows the percentage agreement with the codes, for example where are all coders assigned the same code agreement was seen as 100% (Table 12, Q1, IIN+%), whereas when one person disagreed they were given less than 100% (Table 13, Q3, ALG code = 66% agreement). At times coder 3 has not assigned codes to a particular transcript; this was not disagreement with the assigned codes but rather a lack of confidence with assigning a code. The coders agreed 85% of the time with each other's coding, with the greatest discrepancy identified during discussion being the non-assignment of a code rather than the over assigning of codes.

In addition to the high level of agreement in the inter-rating codings , the validity of the codes are further supported when compared to a study conducted by Overton and Potter[316] which developed a very similar set of codes when studying approaches to solving similar open-ended problems.

4.3 Coding Pencasts

The pencasts were transcribed and the transcripts coded whilst listening to the pencasts using the previously identified codes from section 2.4. The number of occurrences of each code was quantified for each participant and tabulated. To further understand the distribution of approaches used by participants, each approach was normalised by expressing it as a percentage distribution of the total approaches used by the participant.

The codes for CC (Confidence and confusion) were initially set to one side and placed at the end of the table. This is because it was felt that, although an important theme, CC is not an approach but more of a behaviour. The remaining codes were highlighted in light grey if a particular code was within 50% of the participant's most common code. The codes for CC were analysed separately. At times a participant showed no difference between CC+ and CCP-/CCA-. These participants were categorised as being both confident and not confident throughout the process. The codes CCP- and CCA- were analysed to identify whether a participant showed a bias between the two. This was determined by identifying if either CCP- or CCA- were within 50% of each other. Where the codes lay within 50% of each other, both CCA- and CCP- codes were highlighted in dark grey. The final column of the table was analysed using the same process to give the overall profile for the discipline.

The data were also presented in a series of radar charts. This gave a visual representation of percentage distribution of the codes for each participant. The final radar chart for each cohort shows the overall percentage distribution of the codes found for the discipline.

4.3.1 Chemistry Undergraduate Students

Table 14 shows the quantified codes for the undergraduate chemistry participants and shows that the three most frequent codes are:

> IIN+ The participant identified a specific piece of information they think they need. (24.76%)
>
> ALG+ The participant uses calculations and/or equations to solve the problem. (15.51%)
>
> CCP- The participant becomes confused with how to tackle the problem. (11.53%)

The least frequent codes are:

> IPF- The participant does not reflect on the problem creating uncertainty in how to proceed. (0.10%)
>
> IIN- The participant fails to identify a specific piece of information they need. (0.31%)
>
> NDIS+ The participant does not become distracted by context. (0.42%)

Figure 16, Figure 17 and Figure 18 presents the data in Table 14 represented in a series of radar charts. The final radar chart in Figure 18 shows the overall percentage distribution of the codes found for the discipline. In the radar charts the codes that were denoted with a + symbol are represented by the blue line, and the codes denoted with a – symbol are represented by the red line.

Table 14 Chemistry results showing individual counts and percentage distribution of each code

Participants	UHULLCH1		UHULLCH2		UHULLCH3		UHULLCH4		UHULLCH5		UHULLCH6	
Codes	*N=*	*%*	*N=*	*%*	*N=*	*%*	*N=*	*%*	*N=*	*%*	*N=*	*%*
IIN+	12	26.09	15	24.00	9	18.00	20	28.00	11	16.00	4	11.76
A&E+	2	4.35	6	9.52	3	5.88	4	5.63	11	15.49	2	5.88
ALG+	7	15.22	8	12.70	6	11.76	7	9.86	12	16.90	2	5.88
EVA+	3	6.52	3	4.76	0	0.00	2	2.82	5	7.04	0	0.00
IPF+	5	10.87	8	12.70	7	13.73	11	15.49	9	12.68	6	17.68
DAS+	2	4.35	2	3.17	2	3.92	2	2.82	6	8.45	0	0.00
NDIS+	0	0.00	0	0.00	0	0.00	1	1.41	0	0.00	0	0.00
LSA+	0	0.00	1	1.59	0	0.00	1	1.41	2	2.82	0	0.00
IIN-	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	2	5.88
A&E-	4	8.70	0	0.00	2	3.92	3	4.23	2	2.82	0	0.00
ALG-	1	2.17	0	0.00	1	1.96	1	1.41	0	0.00	2	5.88
EVA-	1	2.17	1	1.59	3	5.88	2	2.82	0	0.00	2	5.88
IPF-	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
DAS-	1	2.17	1	1.59	1	1.96	1	1.41	0	0.00	3	8.82
NDIS-	2	4.35	2	3.17	3	5.88	4	5.63	2	2.82	4	11.76
LSA-	3	6.52	2	3.17	3	5.88	2	2.82	1	1.41	3	8.82
CC+	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	2	5.88
CCP-	3	6.52	8	12.70	10	19.61	7	9.86	8	11.27	2	5.88
CCA-	0	0.00	6	9.52	1	1.96	3	4.23	2	2.82	0	0.00

Participants	UHULLCH7		UHULLCH8		UHULLCH9		UHULLCH10		UHULLCH11		UHULLCH12	
Codes	*N=*	*%*	*N=*	*%*	*N=*	*%*	*N=*	*%*	*N=*	*%*	*N=*	*%*
IIN+	14	32.00	12	22.00	11	22.00	13	32.00	16	22.84	16	23.00
A&E+	4	9.09	7	12.73	3	6.00	3	7.32	3	4.29	3	4.23
ALG+	6	13.64	14	25.45	5	10.00	6	14.63	20	28.57	18	25.35
EVA+	3	6.82	6	10.91	0	0.00	0	0.00	2	2.86	1	1.41
IPF+	3	6.82	2	3.64	7	14.00	3	7.32	10	14.29	4	5.63
DAS+	3	6.82	4	7.27	3	6.00	3	7.32	4	5.71	3	4.23
NDIS+	0	0.00	0	0.00	0	0.00	0	0.00	3	4.29	0	0.00
LSA+	1	2.27	0	0.00	2	4.00	0	0.00	2	2.86	0	0.00
IIN-	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
A&E-	0	0.00	0	0.00	0	0.00	1	2.44	1	1.43	1	1.41
ALG-	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
EVA-	2	4.55	1	1.82	3	6.00	3	7.32	2	2.86	1	1.41
IPF-	0	0.00	1	1.82	0	0.00	0	0.00	0	0.00	0	0.00
DAS-	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
NDIS-	1	2.27	0	0.00	2	4.00	0	0.00	0	0.00	1	1.41
LSA-	2	4.55	2	3.64	1	2.00	3	7.32	1	1.43	2	2.82
CC+	0	0.00	1	1.82	2	4.00	2	4.88	2	2.86	0	0.00
CCP-	2	4.55	5	9.09	10	20.00	4	9.76	4	5.71	15	21.13
CCA-	3	6.82	0	0.00	1	2.00	0	0.00	0	0.00	6	8.45

Participants	**USTRACH1**		**USTRACH2**		**USTRACH3**		**USTRACH4**		**USTRACH5**		**Chemistry Overall**	
Codes	*N=*	*%*	*N=*	*%*	*N=*	*%*	*N=*	*%*	*N=*	*%*	*N=*	*%*
IIN+	17	29.00	13	26.00	22	29.00	16	31.00	15	29.00	236	24.76
A&E+	5	8.62	4	8.00	2	2.60	3	5.88	4	7.84	69	7.23
ALG+	7	12.07	8	16.00	9	11.69	4	7.84	9	17.65	148	15.51
EVA+	2	3.45	1	2.00	3	3.90	1	1.96	3	5.88	35	3.67
IPF+	3	5.17	7	14.00	8	10.39	5	9.80	4	7.84	102	10.69
DAS+	2	3.45	3	6.00	5	6.49	2	3.92	3	5.88	49	5.14
NDIS+	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	4	0.42
LSA+	2	3.45	1	2.00	2	2.60	1	1.96	2	3.92	17	1.78
IIN-	1	1.72	0	0.00	0	0.00	0	0.00	0	0.00	3	0.31
A&E-	3	5.17	1	2.00	1	1.30	1	1.96	1	1.96	21	2.20
ALG-	1	1.72	1	2.00	0	0.00	2	3.92	0	0.00	9	0.94
EVA-	1	1.72	2	4.00	1	1.30	2	3.92	0	0.00	27	2.83
IPF-	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	1	0.10
DAS-	1	1.72	0	0.00	0	0.00	1	1.96	0	0.00	9	0.94
NDIS-	3	5.17	1	2.00	3	3.90	3	5.88	0	0.00	31	3.25
LSA-	1	1.72	2	4.00	1	1.30	2	3.92	1	1.96	32	3.35
CC+	1	1.72	1	2.00	0	0.00	1	1.96	0	0.00	12	1.26
CCP-	6	10.34	4	8.00	14	18.18	3	5.88	5	9.80	110	11.53
CCA-	2	3.45	1	2.00	6	7.79	4	7.84	4	7.84	39	4.09

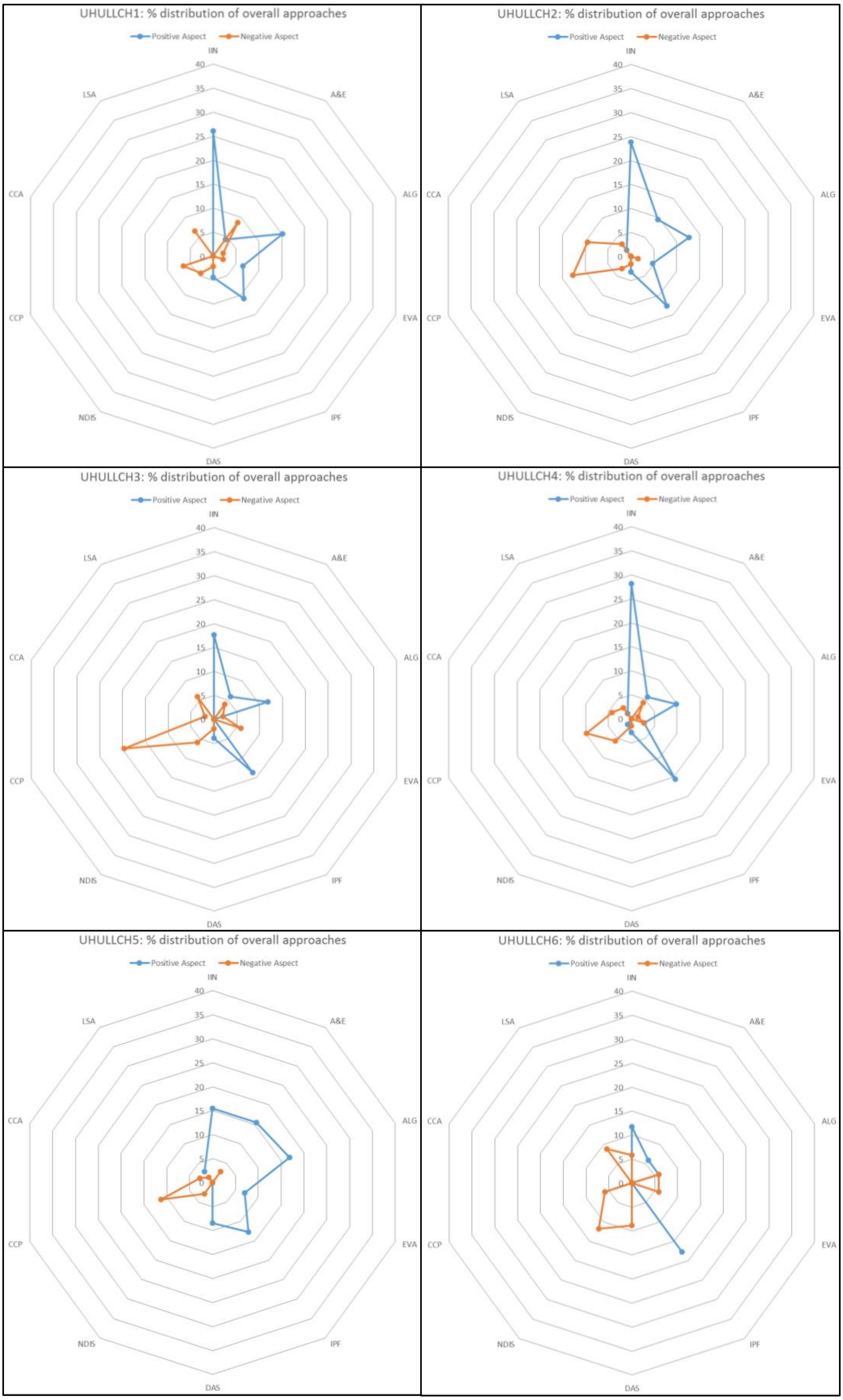

Figure 15 Radar charts displaying the percentage distribution of each approach for chemistry undergraduate participants UHULLCH1 to UHULLCH6.

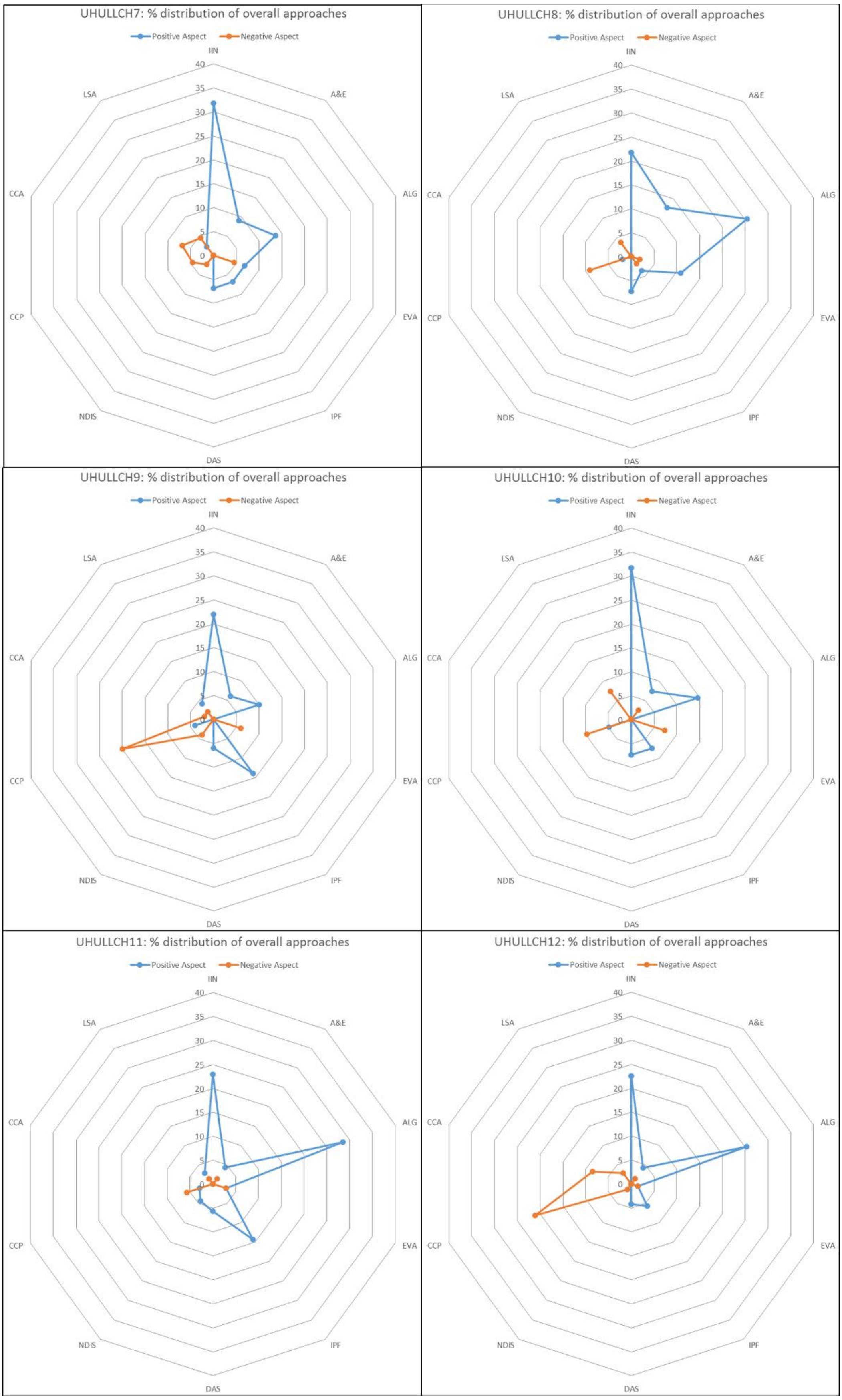

Figure 16 Radar charts displaying the percentage distribution of each approach for chemistry undergraduate participants UHULLCH7 to UHULLCH12

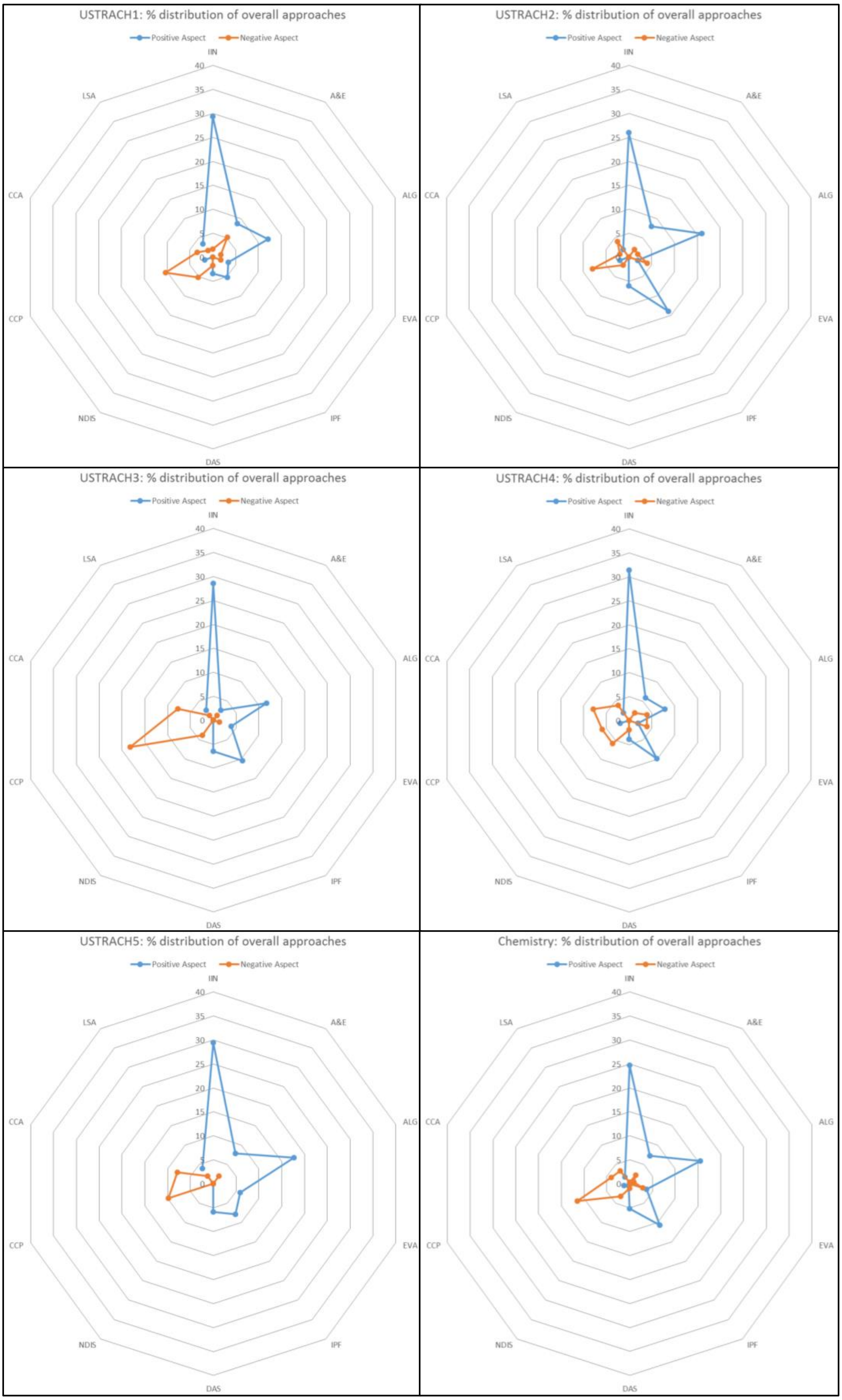

Figure 17 Radar charts displaying the percentage distribution of each approach for chemistry undergraduate participants USTRACH1 to USTRACH5 and their discipline.

It can be seen that most of the participants employed predominantly positive codes, with most of them showing similarly shaped radar charts. There are only two radar charts that don't look similar to the rest, participants UHULLCH6 and UHULLCH8. UHULlCH6 shows that there is a similar distribution between positive and negative codes with little elongation along IIN+ and ALG+ codes. UHULLCH8 shows a similar distribution of positive approaches seen in most other participants. However, there is a greater extension along the EVA+ and A&E+ codes.

Figure 19 compares the overall profiles of participants who answered the questions in the conventional order (SET1) and those who answered them in an alternative order (SET2).

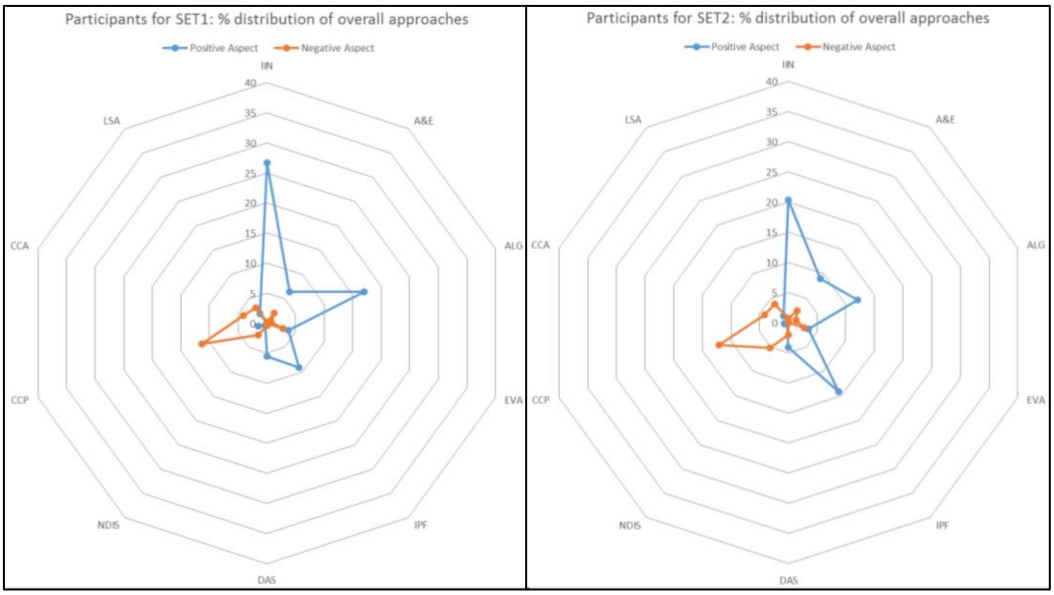

Figure 18 Comparison between participants who answered the conventional order of questions (SET1) and the alternative order of questions (SET2)

Figure 19 clearly shows that there is a very little difference in the prominent codes emerging between SET1 and SET2 participants, although the is a slight shift in proportions. SET2 participants show a highest preference for IPF+ and

SET1 participants show a higher preference for IIN+, however, the overall shape of the chart is similar.

For chemistry SET1 participants, the first problem was answered in four different ways; a) guessing a suitable ratio of people to toilets, b) assessing the load capacity of the toilet and therefore how many uses a toilet can accommodate and c) assessing the amount of effluence produced by individuals and then calculating the maximum number of toilets needed and d) time spent in a toilet.

The second problem was answered in three different ways; a) assumption that one revolution of the tyre would be sufficient to degrade the tyre and b) a rate of degradation over the lifetime of the tyre and c) requiring a friction coefficient of either the rubber of the tyre or the road surface.

The third problem was answered in three different ways a) using the equation PV = *n*RT, b) calculating the volume of the Earth and multiply by density and c) calculate the number of moles of gas using the volume of the Earth.

4.3.2 Physics Undergraduate Students

Table 15 shows the quantified and percentage occurrence of codes for the physics undergraduates and shows that the three most frequent codes are:

IIN+ The participant identified a specific piece of information they think they need. (24.14%)

ALG+ The participant uses calculations and/or equations to solve the problem. (16.77%)

IPF+ The participant reflects on what is being asked in the problem. (11.76%)

The lowest frequency codes are

IIN- The participant fails to identify a specific piece of information they need. (0%)

ALG- The participant does not use calculations and/or equations to solve the problem. (0.27%)

IPF- The participant does not reflect on the problem creating uncertainty in how to proceed. (0.27%)

DAS- The participant does not develop a clear strategy. (0.27%)

(four have been assigned as the lowest codes in this instance because three codes were joint second lowest):

Figure 20, Figure 21 and Figure 22 presents the data in Table 15 as a series of radar charts. The final radar chart in Figure 22 shows the overall percentage distribution of the codes found for the discipline.

Table 15 Physics results showing individual counts and percentage distribution of each code

Participants	UHULLPH1		UHULLPH2		UHULLPH3		UHULLPH4		UHULLPH5		UHULLPH6	
Codes	*N=*	*%*	*N=*	*%*	*N=*	*%*	*N=*	*%*	*N=*	*%*	*N=*	*%*
IIN+	19	33.92	9	18.00	14	31.81	14	36.88	20	34.51	15	14.29
A&E+	5	8.93	6	12.00	4	9.09	1	2.63	7	12.07	9	8.57
ALG+	9	16.07	9	18.00	3	6.82	3	7.89	10	17.24	25	23.81
EVA+	0	0.00	3	6.00	4	9.09	1	2.63	1	1.72	5	4.76
IPF+	5	8.93	3	6.00	3	6.82	2	5.26	6	10.34	21	20.00
DAS+	3	5.36	3	6.00	3	6.82	1	2.63	3	5.17	3	2.86
NDIS+	0	0.00	0	0.00	2	4.55	0	0.00	0	0.00	2	1.90
LSA+	3	5.36	3	6.00	2	4.55	1	2.63	3	5.17	3	2.86
IIN-	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
A&E-	1	1.79	0	0.00	1	2.27	2	5.26	1	1.72	4	3.81
ALG-	0	0.00	0	0.00	0	0.00	2	5.26	0	0.00	0	0.00
EVA-	3	5.36	1	2.00	0	0.00	2	5.26	2	3.45	1	0.95
IPF-	0	0.00	0	0.00	0	0.00	1	2.63	0	0.00	0	0.00
DAS-	0	0.00	0	0.00	0	0.00	2	5.26	0	0.00	0	0.00
NDIS-	0	0.00	3	6.00	1	2.27	0	0.00	1	1.72	3	2.86
LSA-	0	0.00	0	0.00	1	2.27	2	5.26	0	0.00	0	0.00
CC+	0	0.00	0	0.00	1	2.27	1	2.63	1	1.72	0	0.00
CCP-	4	7.14	9	18.00	3	6.82	3	7.89	3	5.17	12	11.43
CCA-	4	7.14	1	2.00	2	4.55	0	0.00	0	0.00	2	1.90

Participants	**UHULLPH7**		**UHULLPH8**		**UHULLPH9**		**UHULLPH10**		**UEDINPH1**		**UEDINPH2**	
Codes	*N=*	*%*	*N=*	*%*	*N=*	*%*	*N=*	*%*	*N=*	*%*	*N=*	*%*
IIN+	8	16.00	18	15.95	24	26.09	24	23.77	15	25.87	17	37.80
A&E+	6	12.00	14	12.39	8	8.70	10	9.90	8	13.79	3	6.67
ALG+	12	24.00	30	26.55	25	27.17	17	16.83	10	17.24	4	8.89
EVA+	1	2.00	5	4.42	3	3.26	3	2.97	1	1.72	1	2.22
IPF+	8	16.00	18	15.93	12	13.04	15	14.85	4	6.90	4	8.89
DAS+	3	6.00	8	7.08	4	4.35	5	4.95	4	6.90	2	4.44
NDIS+	3	6.00	1	0.88	1	1.09	1	0.99	0	0.00	0	0.00
LSA+	2	4.00	3	2.65	3	3.26	3	2.97	3	5.17	2	4.44
IIN-	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
A&E-	0	0.00	0	0.00	3	3.26	1	0.99	0	0.00	1	2.22
ALG-	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	1	2.22
EVA-	2	4.00	0	0.00	0	0.00	1	0.99	2	3.45	2	4.44
IPF-	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
DAS-	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	1	2.22
NDIS-	0	0.00	3	2.65	2	2.17	4	3.96	2	3.45	0	0.00
LSA-	1	2.00	0	0.00	0	0.00	0	0.00	0	0.00	1	2.22
CC+	2	4.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
CCP-	2	4.00	11	9.73	6	6.52	15	14.85	8	13.79	4	8.89
CCA-	0	0.00	2	1.77	1	1.09	2	1.98	1	1.72	2	4.44

Participants	UEDINPH3		UEDINPH4		UEDINPH5		UEDINPH6		UEDINPH7		Physics Overall	
Codes	*N=*	*%*	*N=*	*%*	*N=*	*%*	*N=*	*%*	*N=*	*%*	*N=*	*%*
IIN+	15	24.18	12	22.22	15	23.07	9	21.45	19	29.67	267	24.14
A&E+	6	9.68	3	5.56	4	6.15	7	16.67	11	17.19	112	10.21
ALG+	6	9.68	6	11.11	5	7.69	4	9.52	6	9.38	184	16.77
EVA+	3	4.84	4	7.41	2	3.08	3	7.14	2	3.13	42	3.83
IPF+	6	9.68	8	14.81	8	12.31	2	4.76	4	6.25	129	11.76
DAS+	3	4.84	3	5.56	4	6.15	3	7.14	3	4.69	58	5.29
NDIS+	3	4.84	3	5.56	3	4.62	3	7.14	2	3.13	24	2.19
LSA+	3	4.84	3	5.56	3	4.62	3	7.14	3	4.69	46	4.19
IIN-	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
A&E-	0	0.00	1	1.85	1	1.54	0	0.00	1	1.56	17	1.55
ALG-	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	3	0.27
EVA-	1	1.61	1	1.85	1	1.54	1	2.38	1	1.56	21	1.91
IPF-	0	0.00	0	0.00	0	0.00	1	2.38	1	1.56	3	0.27
DAS-	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	3	0.27
NDIS-	0	0.00	0	0.00	1	1.54	0	0.00	1	1.56	21	1.91
LSA-	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	5	0.46
CC+	0	0.00	1	1.85	0	0.00	0	0.00	1	1.56	7	0.64
CCP-	9	14.52	8	14.81	18	27.69	3	7.14	6	9.38	124	11.30
CCA-	7	11.29	1	1.85	0	0.00	3	7.14	3	4.69	31	2.83

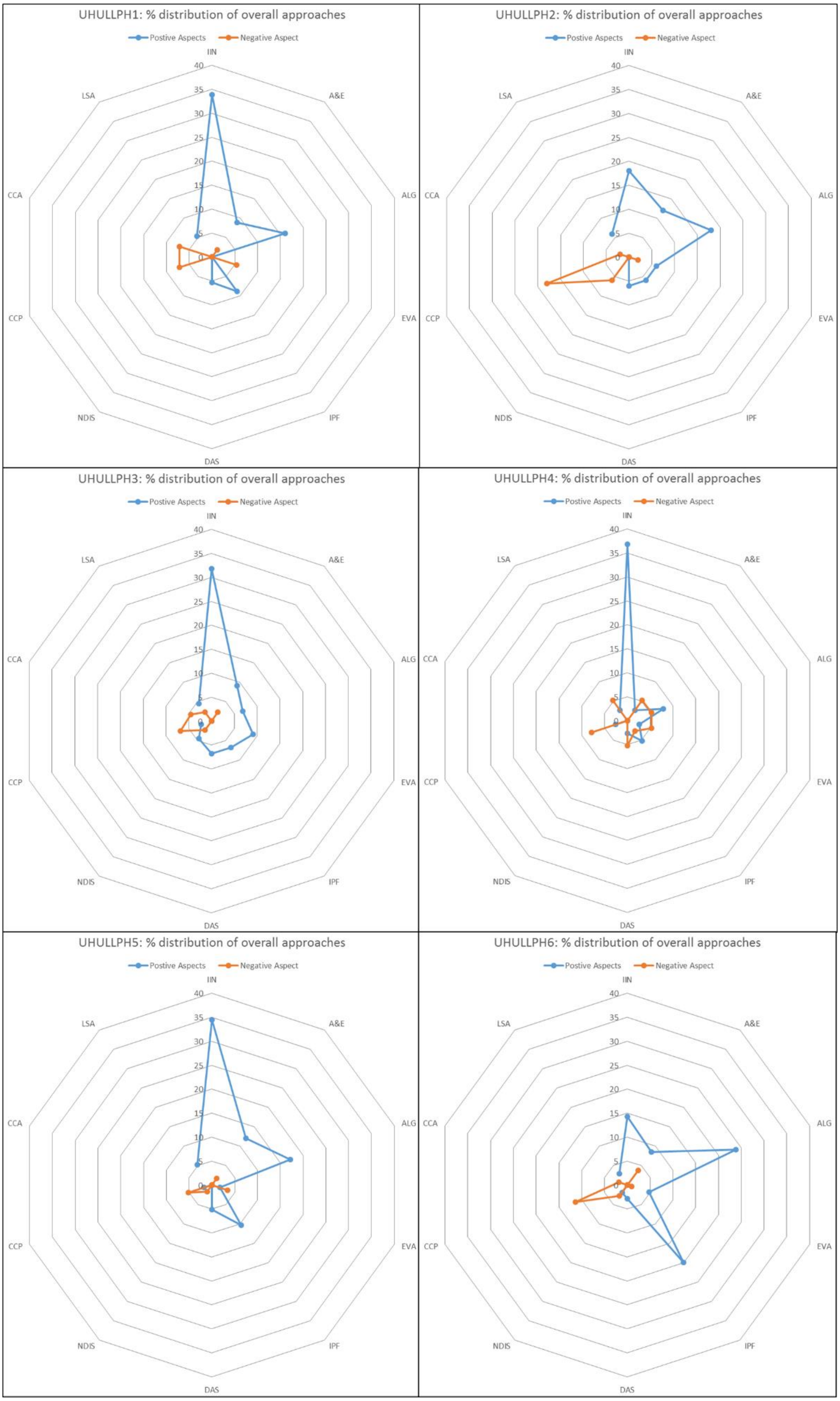

Figure 19 Radar charts displaying the percentage distribution of each approach for physics undergraduate participants UHULLPH1 to UHULLPH6.

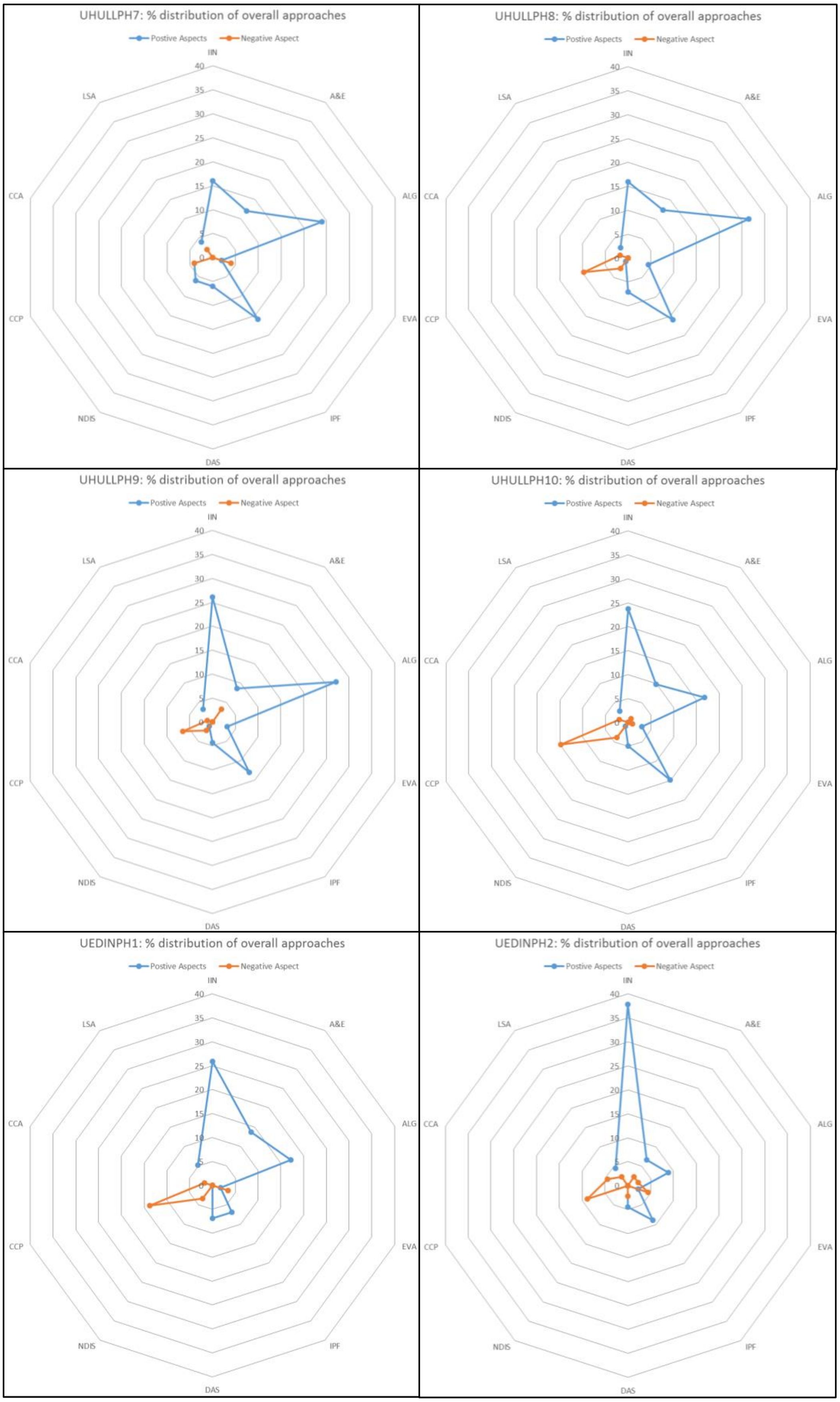

Figure 20 Radar charts displaying the percentage distribution of each approach for physics undergraduate participants UHULLPH7 to UEDINPH2.

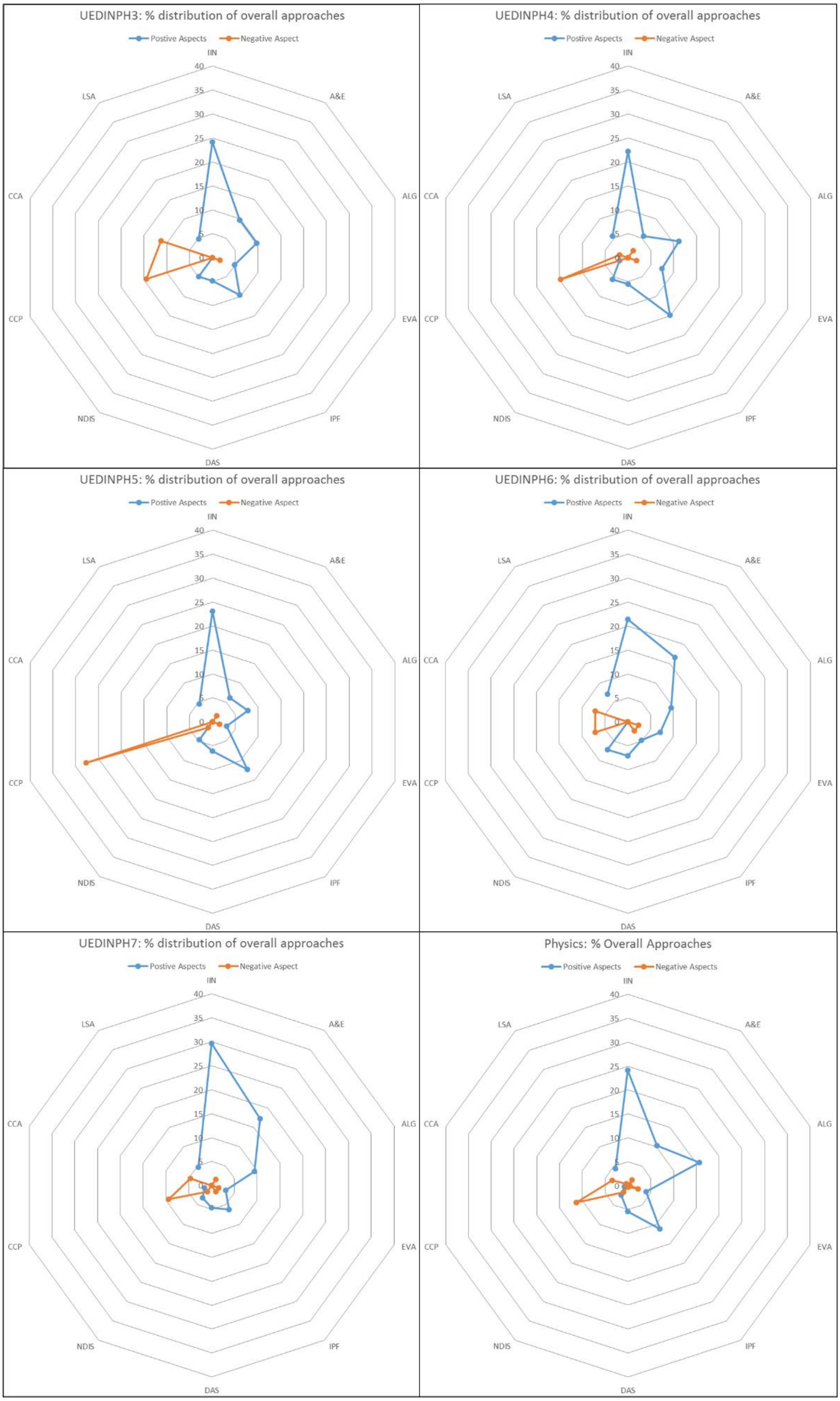

Figure 21 Radar charts displaying the percentage distribution of each approach for physics undergraduate participants UEDINPH3 to UEDINPH7 and overall discipline specific radar chart.

From Figure 20, Figure 21 and Figure 22, we can see that most of the participants employ predominantly positive codes, with most of them showing similarly shaped radar charts to that found in the discipline overall chart. Two radar charts appear to be different from the others. UHULLPH3 shows greater elongation along the EVA+ code, which indicates that this participant employed more evaluative processes. UEDINPH6 shows greater elongation in the NDIS+ code and retraction along the IPF+ over other participants.

Figure 23 shows the overall profiles between participants that answered the original set of questions (SET3) and those that answered an alternative set of questions (SET4).

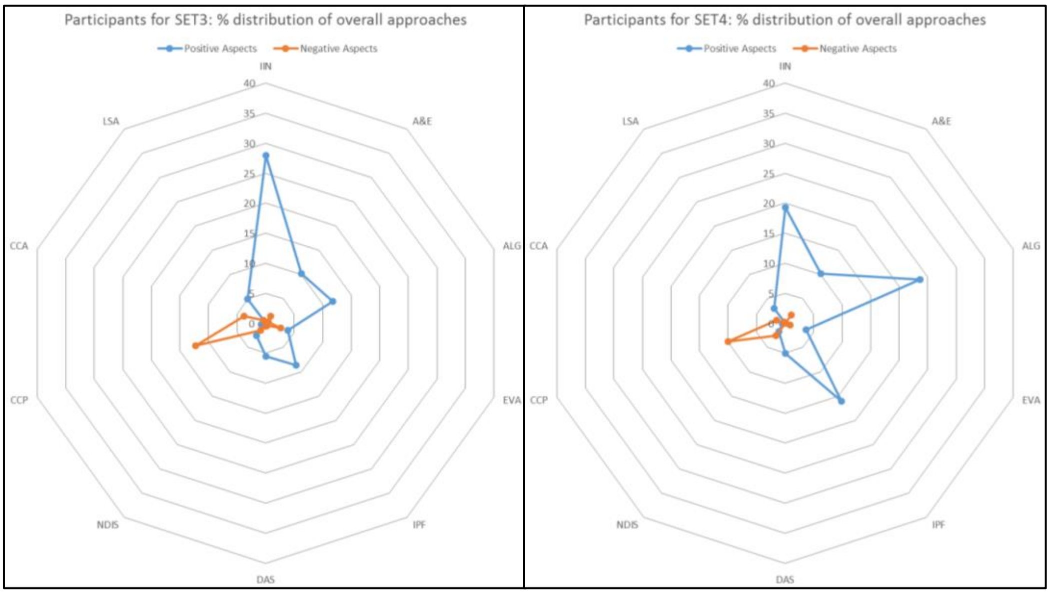

Figure 22 Comparison between participants who answered the original question set (SET3) and the alternative question set (SET4)

Figure 23 shows that there is a slight difference in the proportion of approaches used by SET4 when compared against SET3. There is a definite emergence of ALG+ in the SET4 participants, whereas SET3 shows a higher preference for IIN+. However the general shape appears to be the similar.

For physics SET3 participants, the first problem was answered in four different ways; a) guessing a suitable ratio of people to toilets, b) assessing the load capacity of the toilet and therefore how many uses a toilet can accommodate and c) assessing the amount of effluence produced by individuals and then calculating the maximum number of toilets needed and d) time spent in a toilet.

The second problem was answered in three different ways; a) assumption that one revolution of the tyre would be sufficient to degrade the tyre and b) a rate of degradation over the lifetime of the tyre and c) requiring a friction coefficient of either the rubber of the tyre or the road surface.

The third problem was answered in three different ways a) using the equation PV = *n*RT, b) calculating the volume of the Earth and multiply by density and c) calculate the number of moles of gas using the volume of the Earth.

For physics SET4 participants the problems the first problem was answered in two different ways a) using the equation distance over time for the average speed of the runner and b) other participants answered the problem using the equation for kinetic energy.

The second problem was answered in three different ways a) calculating the volume of gas produced by an estimated 50kg of helium and b) guessing the volume of gas required per party balloon and guessing the amount of gas produced by 96000 litres would produce and c) calculating the amount of gas produced by 96tons of helium.

The third problem was answered in two separate ways a) the percentage difference of the masses and thus the percentage fuel saved and b) the ratio of mass difference and then the ratio of different fuel used.

4.3.3 Sports Rehabilitation Undergraduate Students

Table 16 shows the quantified codes for sports rehabilitation undergraduates and shows that the three highest frequency codes are:

IIN+ The participant identified a specific piece of information they think they need. (13.34%)

CCP- The participant becomes confused with how to tackle the problem. (10.13%)

A&E+ The participant makes realistic estimations of numerical values, approximations are made to ease calculations. (8.37%)

The lowest frequency codes for sports rehabilitation undergraduate students are:

LSA+ The participant employs a logically progressive strategy and/or grounded in scientific reasoning. (0%)

NDIS- The student becomes distracted by context. (0.88%)

EVA+ The participant evaluates their strategy and/or their final answer. (1.32%)

Figure 24 and Figure 25 presents the data in Table 16 in a series of radar charts.

Table 16 Sports rehabilitation results showing individual counts and percentage distribution of each code

Participants	UHULLSR1		UHULLSR2		UHULLSR3		UHULLSR4		UHULLSR5		UHULLSR6	
Codes	*N=*	*%*	*N=*	*%*	*N=*	*%*	*N=*	*%*	*N=*	*%*	*N=*	*%*
IIN+	1	3.13	4	12.89	1	3.45	11	21.15	8	19.48	4	9.30
A&E+	1	3.13	1	3.23	2	6.90	3	5.77	4	9.76	8	18.59
ALG+	0	0.00	2	6.45	0	0.00	0	0.00	1	2.44	6	13.95
EVA+	0	0.00	0	0.00	0	0.00	2	3.85	0	0.00	1	2.33
IPF+	1	3.13	0	0.00	3	10.34	5	9.62	4	9.76	5	11.63
DAS+	1	3.13	2	6.45	1	3.45	3	5.77	1	2.44	3	6.98
NDIS+	3	9.38	3	9.68	3	10.34	1	1.92	3	7.32	3	6.98
LSA+	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
IIN-	3	9.38	1	3.23	2	6.90	0	0.00	0	0.00	0	0.00
A&E-	2	6.25	4	12.89	2	6.90	2	3.85	2	4.88	2	4.65
ALG-	3	9.38	1	3.23	3	10.34	3	5.77	2	4.88	1	2.33
EVA-	3	9.38	3	9.68	3	10.34	1	1.92	3	7.32	2	4.65
IPF-	2	6.25	3	9.68	0	0.00	0	0.00	0	0.00	0	0.00
DAS-	2	6.25	1	3.23	2	6.90	0	0.00	2	4.88	0	0.00
NDIS-	0	0.00	0	0.00	0	0.00	2	3.85	0	0.00	0	0.00
LSA-	3	9.38	3	9.68	3	10.34	3	5.77	3	7.32	3	6.98
CC+	1	3.13	2	6.45	1	3.45	0	0.00	0	0.00	1	2.33
CCP-	1	3.13	0	0.00	1	3.45	12	23.07	5	12.20	4	9.30
CCA-	5	15.57	1	3.23	2	6.90	4	7.69	3	7.32	0	0.00

Participants	Sports Rehab Overall	
Codes	*N=*	*%*
IIN+	29	12.73
A&E+	19	8.33
ALG+	9	3.95
EVA+	3	1.32
IPF+	18	7.89
DAS+	11	4.82
NDIS+	16	7.02
LSA+	0	0.00
IIN-	6	2.63
A&E-	14	6.14
ALG-	13	5.70
EVA-	15	6.58
IPF-	5	2.19
DAS-	7	3.07
NDIS-	2	0.88
LSA-	18	7.89
CC+	5	2.19
CCP-	23	10.09
CCA-	15	6.58

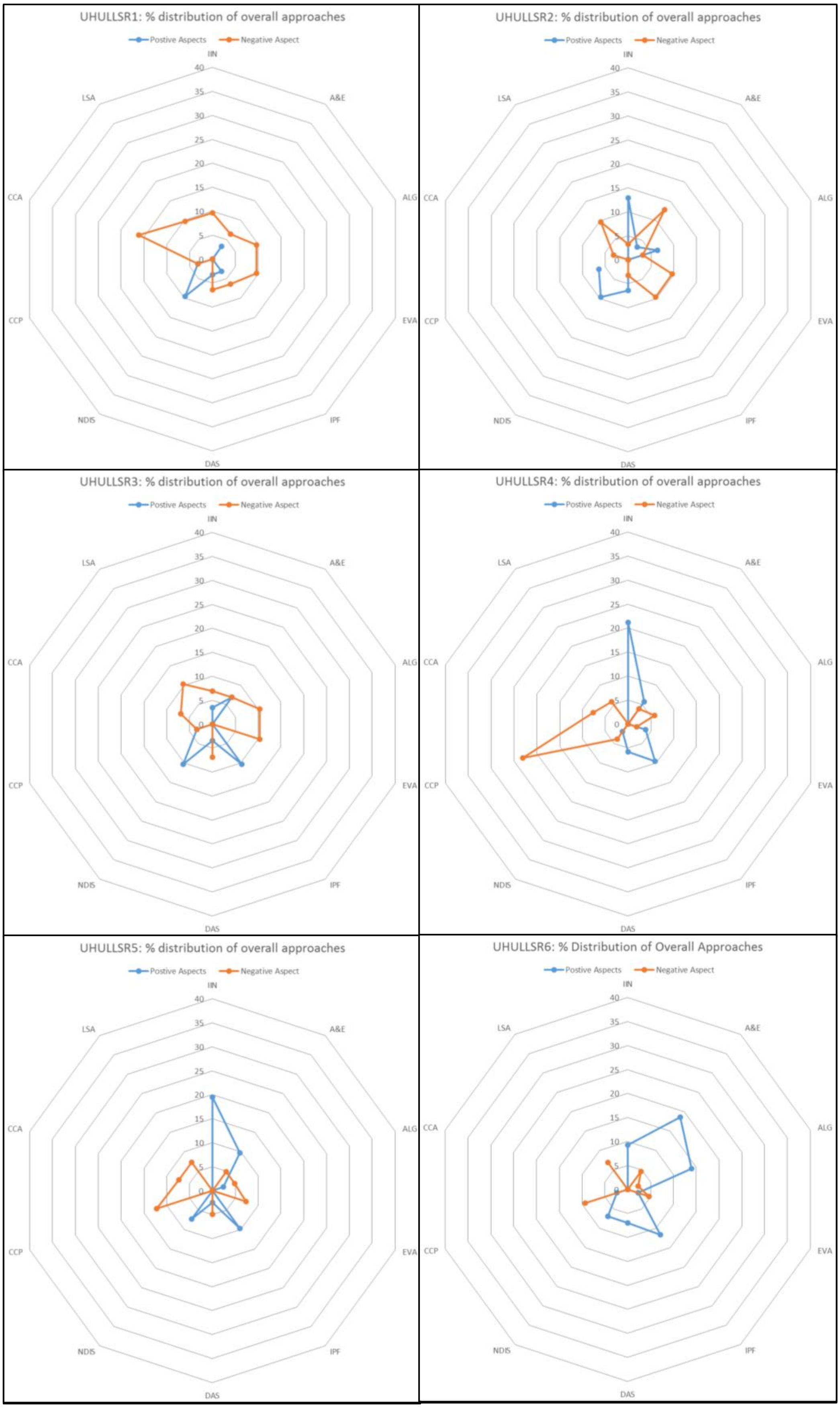

Figure 23 Radar charts displaying the percentage distribution of each approach for sports rehabilitation undergraduate participants UHULLSR1 to UHULLSR6

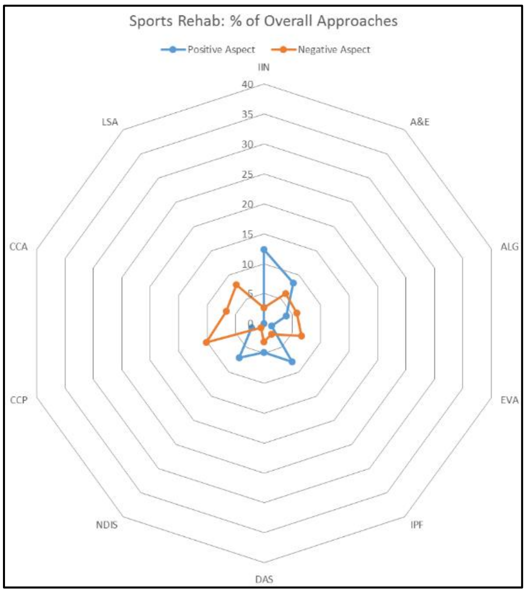

Figure 24 Radar chart displaying the percentage distribution of overall approaches for sports rehabilitation

Figure 24 shows that there is very little similarity between the participants studying sports rehabilitation, with UHULLSR5 being the only participant to have a chart that completely resembled the discipline one. Other participants, all have some characteristics that resemble the discipline chart with most presenting elongation along the CCP-/CCA- code. This analysis has to be treated with caution due to the small number of participants involved with the study.

Sports rehabilitation participants answered problem 1 in three different ways a) outright guess at an answer, b) reasoning toilets per site and how many sites and c) guess at a suitable ratio of toilets to people.

Problem 2 was answered in two different ways, these were a) a guess with limited to no reasoning and b) a rate of loss based on a concentration

Problem 3 was answered in two different ways these were a) outright guess and b) calculating a rate based on how many breaths per minute and percentage of CO_2.

4.3.4 Psychology Undergraduate Students

Table 17 shows the quantified codes for the psychology undergraduates and shows that the three highest frequency codes are:

> CCP- The participant becomes confused with how to tackle the problem. (10.99%)
>
> IPF+ The participant reflects on what is being asked in the problem. (9.15%)
>
> A&E+ The participant makes realistic estimations of numerical values, approximations are made to ease calculations. (8.23%)

The lowest frequency codes for psychology undergraduate students are:

> LSA+ The participant employs a logically progressive strategy and/or grounded in scientific reasoning. (0.30%)
>
> ALG+ The participant uses calculations and/or equations to solve the problem. (0.30%)
>
> EVA+ The participant evaluates their strategy and/or their final answer. (0.61%)

Figure 26 and Figure 27 presents the data in Table 17 in a series of radar charts.

Table 17 Psychology results showing individual counts and percentage distribution of each code

Participants	UHULLPS1		UHULLPS2		UHULLPS3		UHULLPS4		UHULLPS5		UHULLPS6	
Codes	*N=*	*%*	*N=*	*%*	*N=*	*%*	*N=*	*%*	*N=*	*%*	*N=*	*%*
IIN+	1	2.78	0	0.00	6	12.24	0	0.00	4	9.09	5	11.63
A&E+	3	8.33	2	7.14	9	18.39	3	9.68	1	2.27	1	2.33
ALG+	1	2.78	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
EVA+	0	0.00	1	3.57	1	2.04	0	0.00	0	0.00	0	0.00
IPF+	1	2.78	1	3.57	5	16.33	2	6.45	11	24.99	2	4.65
DAS+	3	8.33	1	3.57	3	6.12	2	6.45	1	2.27	0	0.00
NDIS+	3	8.33	3	10.72	1	2.04	2	6.45	0	0.00	0	0.00
LSA+	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
IIN-	2	5.56	3	10.72	1	2.04	3	9.68	0	0.00	1	2.33
A&E-	2	5.56	2	7.14	0	0.00	4	12.88	2	4.55	3	6.98
ALG-	2	5.56	3	10.72	3	6.12	3	9.68	3	6.82	3	6.98
EVA-	3	8.33	2	7.14	2	4.08	3	9.68	3	6.82	3	6.98
IPF-	2	5.56	2	7.14	0	0.00	1	3.23	0	0.00	1	2.33
DAS-	0	0.00	2	7.14	0	0.00	1	3.23	2	4.55	3	6.98
NDIS-	0	0.00	0	0.00	3	6.12	1	3.23	6	13.64	7	16.28
LSA-	3	8.33	3	10.71	3	6.12	3	9.68	3	6.82	3	6.98
CC+	0	0.00	3	10.72	1	2.04	3	9.68	0	0.00	0	0.00
CCP-	8	22.21	0	0.00	3	6.12	0	0.00	8	18.18	9	20.90
CCA-	2	5.56	0	0.00	5	10.20	0	0.00	0	0.00	2	4.65

Participants	UHULLPS7		UHULLPS8		UHULLPS9		Psychology Overall	
Codes	*N=*	*%*	*N=*	*%*	*N=*	*%*	*N=*	*%*
IIN+	3	9.09	4	10.26	0	0.00	23	7.01
A&E+	2	6.06	4	10.26	2	7.14	27	8.23
ALG+	0	0.00	0	0.00	0	0.00	1	0.30
EVA+	0	0.00	0	0.00	0	0.00	2	0.61
IPF+	0	0.00	7	17.96	1	3.57	30	9.15
DAS+	0	0.00	3	7.69	1	3.57	14	4.27
NDIS+	3	9.09	0	0.00	3	10.72	15	4.57
LSA+	0	0.00	1	2.56	0	0.00	1	0.30
IIN-	1	3.03	1	2.56	3	10.72	15	4.57
A&E-	3	9.09	2	5.13	2	7.14	20	6.10
ALG-	3	9.09	3	7.69	3	10.72	26	7.93
EVA-	3	9.09	3	7.69	3	10.72	25	7.62
IPF-	3	9.09	0	0.00	2	7.14	11	3.35
DAS-	3	9.09	0	0.00	2	7.14	13	3.96
NDIS-	0	0.00	5	12.82	0	0.00	22	6.71
LSA-	3	9.09	2	5.13	3	10.71	26	7.93
CC+	0	0.00	1	2.56	2	7.14	10	3.05
CCP-	5	15.16	2	5.13	1	3.57	36	10.99
CCA-	1	3.03	1	2.56	0	0.00	11	3.35

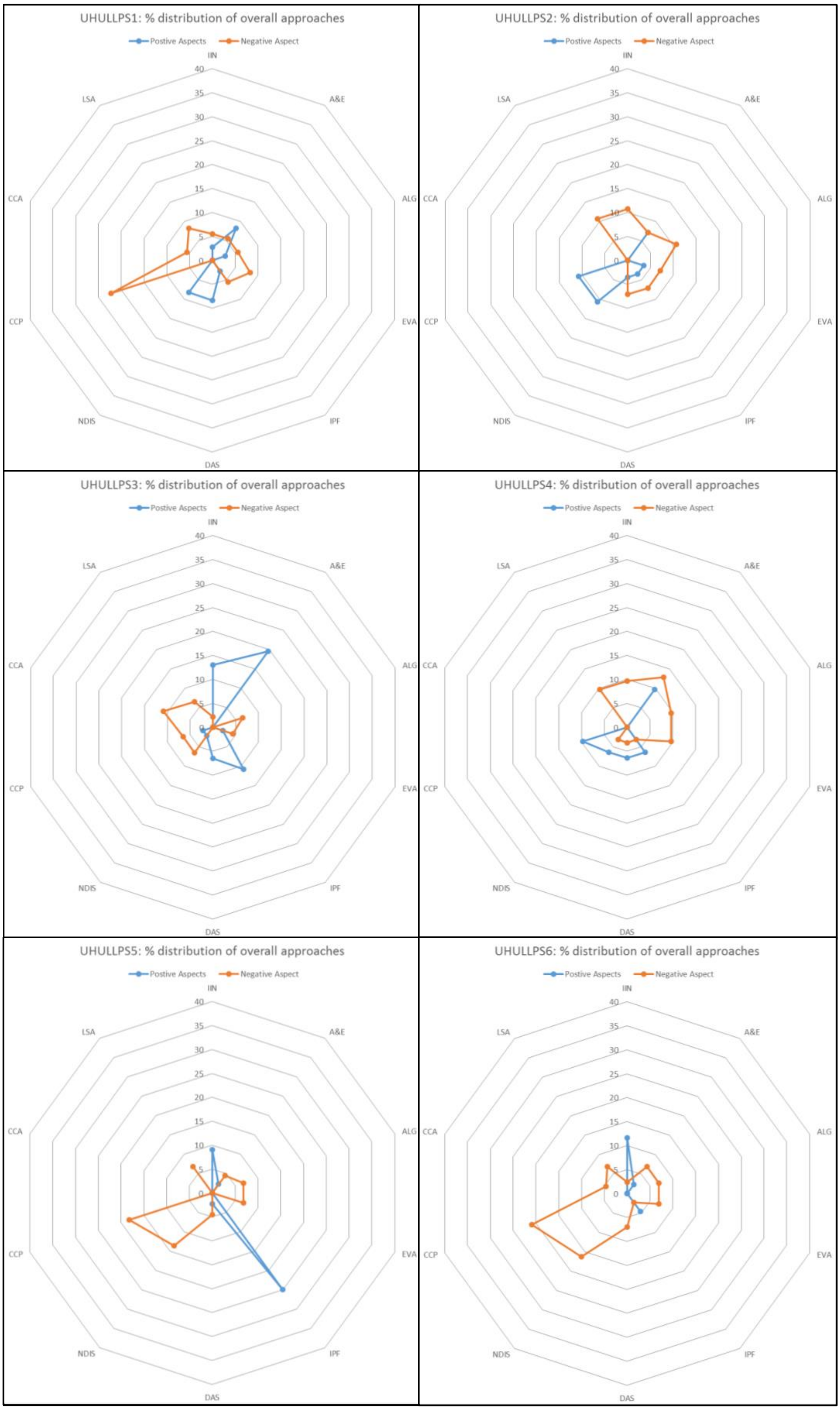

Figure 25 Radar charts displaying the percentage distribution of each approach for psychology undergraduate participants UHULLPS1 to UHULLPS6

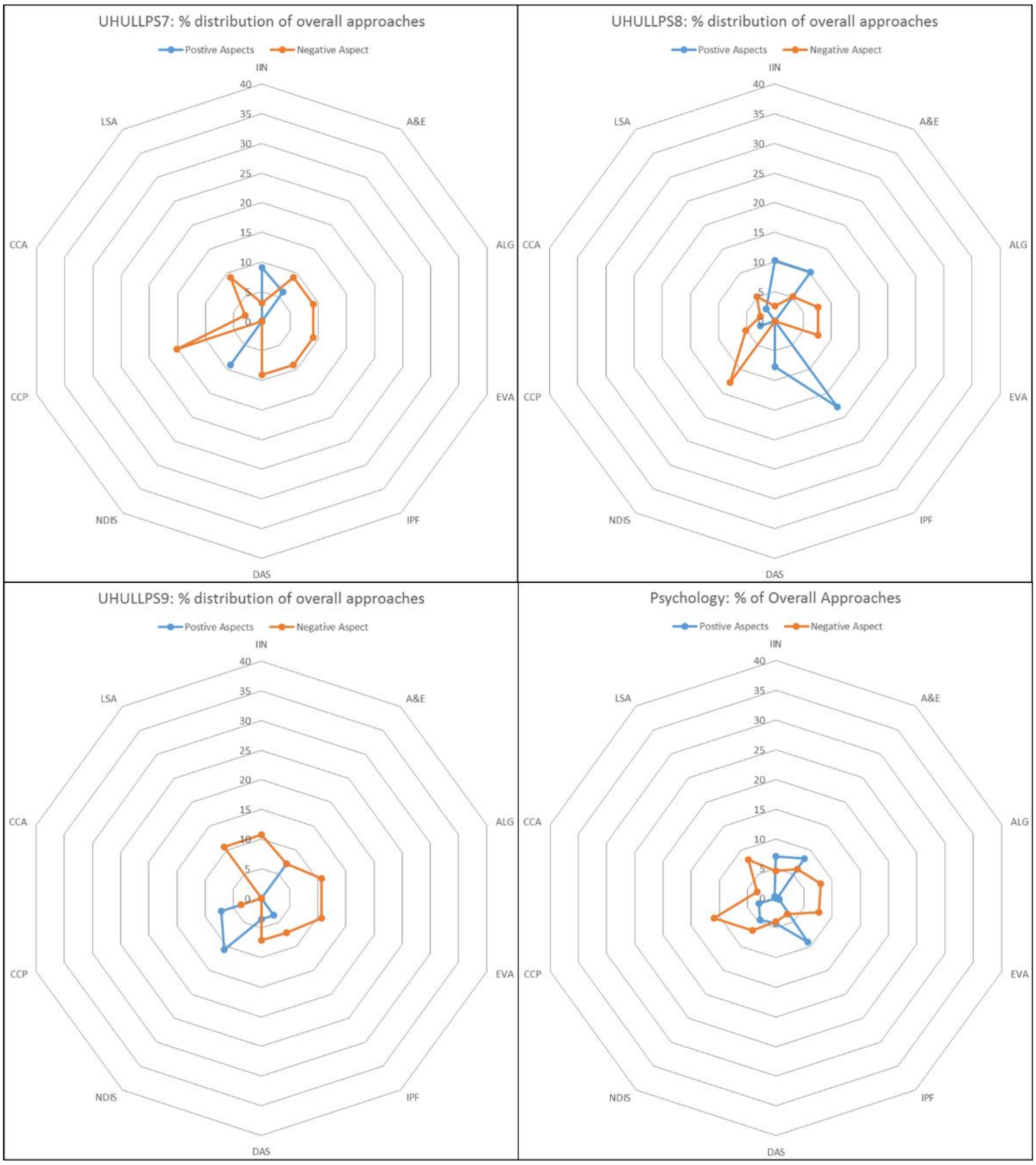

Figure 26 Radar charts displaying the percentage distribution of each approach for psychology undergraduate participants UHULLPS7 to UHULLPS9 and as an entire discipline.

Figure 26 and Figure 27 shows that there is very little commonality between psychology participants other than them all presenting EVA- and ALG- codes. However, it should be noted that the sample size for the psychology participants was small (*n*=9) and this small sample size may contribute to the lack of a consistent profile amongst the psychology participants.

For psychology participants problem 1 was answered in three different ways a) number of people multiplied by the number of days b) guessing with varying amounts of reasoning and c) how many times people would require the toilet of a set period of time.

Problem 2 was answered in three different ways, these were a) guess work, b) Using experience and extrapolating and c) none numerical reasoning

Problem 3 was answered in four different ways these were a) guess work using numerical reasoning, for example does that sound like a reasonable value?, b) guess work using percentage distribution amongst the population, c) none numerical reasoning and d) guessing a ratio.

4.3.5 Inter-Disciplinary Science Undergraduate Students

Table 18 shows the quantified codes for the inter-disciplinary science undergraduates and shows that the three highest frequency codes are:

IIN+ The participant identified a specific piece of information they think they need. (24%)

IPF+ The participant reflects on what is being asked in the problem. (14%)

ALG+ The participant uses calculations and/or equations to solve the problem. (12%)

The lowest frequency codes for inter-disciplinary science undergraduate students are:

IPF- The participant does not reflect on the problem creating uncertainty in how to proceed. (0%)

NDIS+ The participant does not become distracted by context. (0%)

IIN- The participant fails to identify a specific piece of information they need. (0%)

Figure 28 and Figure 29 presents the data in Table 18 in a series of radar charts.

Table 18 Inter-disciplinary science results showing individual counts and percentage distribution of each code

Participants	ULEIISCI1		ULEIISCI2		ULEIISCI3		ULEIISCI4		ULEIISCI5		ULEIISCI6	
Codes	*N=*	*%*	*N=*	*%*	*N=*	*%*	*N=*	*%*	*N=*	*%*	*N=*	*%*
IIN+	5	12.50	8	24.97	15	31.25	18	20.45	35	28.92	10	18.18
A&E+	5	12.50	5	15.63	5	10.42	8	9.09	15	12.40	8	14.55
ALG+	5	12.50	3	9.38	1	2.08	13	14.77	17	14.05	7	12.73
EVA+	1	2.50	0	0.00	1	2.08	6	6.82	8	6.61	5	9.09
IPF+	7	17.50	3	9.38	9	18.75	14	15.91	14	11.57	7	12.73
DAS+	2	5.00	3	9.38	0	0.00	5	5.68	5	4.13	3	5.45
NDIS+	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
LSA+	2	5.00	2	6.25	0	0.00	3	3.41	3	2.48	2	3.64
IIN-	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
A&E-	1	2.50	0	0.00	0	0.00	3	3.41	3	2.48	4	7.27
ALG-	0	0.00	0	0.00	2	4.17	0	0.00	0	0.00	0	0.00
EVA-	2	5.00	3	9.38	2	4.17	2	2.27	1	0.83	0	0.00
IPF-	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
DAS-	1	2.50	0	0.00	3	6.25	0	0.00	0	0.00	0	0.00
NDIS-	1	2.50	0	0.00	4	8.33	3	3.41	2	1.65	0	0.00
LSA-	1	2.50	1	3.13	3	6.25	0	0.00	0	0.00	1	1.82
CC+	3	7.50	2	6.25	3	6.25	0	0.00	0	0.00	0	0.00
CCP-	1	2.50	2	6.25	0	0.00	12	13.64	12	9.92	5	9.09
CCA-	3	7.50	0	0.00	0	0.00	1	1.14	6	4.96	3	5.45

Participants	ULEIISCI7		Interdisciplinary Science Overall	
Codes	*N=*	*%*	*N=*	*%*
IIN+	10	24.37	101	23.76
A&E+	5	12.20	51	12.00
ALG+	6	14.63	52	12.24
EVA+	0	0.00	21	4.94
IPF+	4	9.76	58	13.65
DAS+	3	7.32	21	4.94
NDIS+	0	0.00	0	0.00
LSA+	3	7.32	15	3.53
IIN-	0	0.00	0	0.00
A&E-	1	2.44	12	2.82
ALG-	1	2.44	3	0.71
EVA-	3	7.32	13	3.06
IPF-	0	0.00	0	0.00
DAS-	0	0.00	4	0.94
NDIS-	1	2.44	11	2.59
LSA-	0	0.00	6	1.41
CC+	0	0.00	8	1.88
CCP-	1	2.44	33	7.76
CCA-	3	7.32	16	3.76

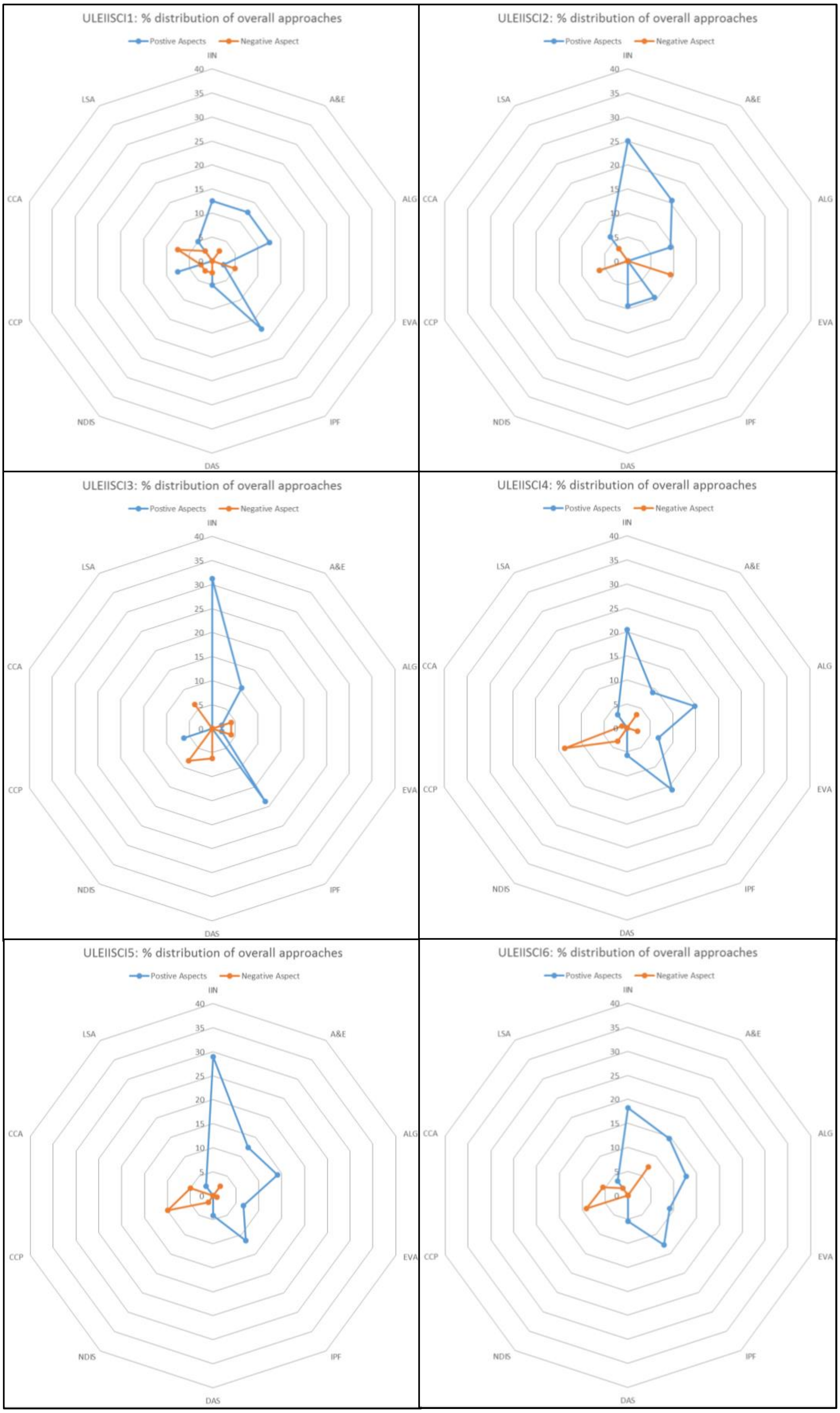

Figure 27 Radar charts displaying the percentage distribution of each approach for each interdisciplinary science undergraduate participants ULEISCI1 to ULEISCI6.

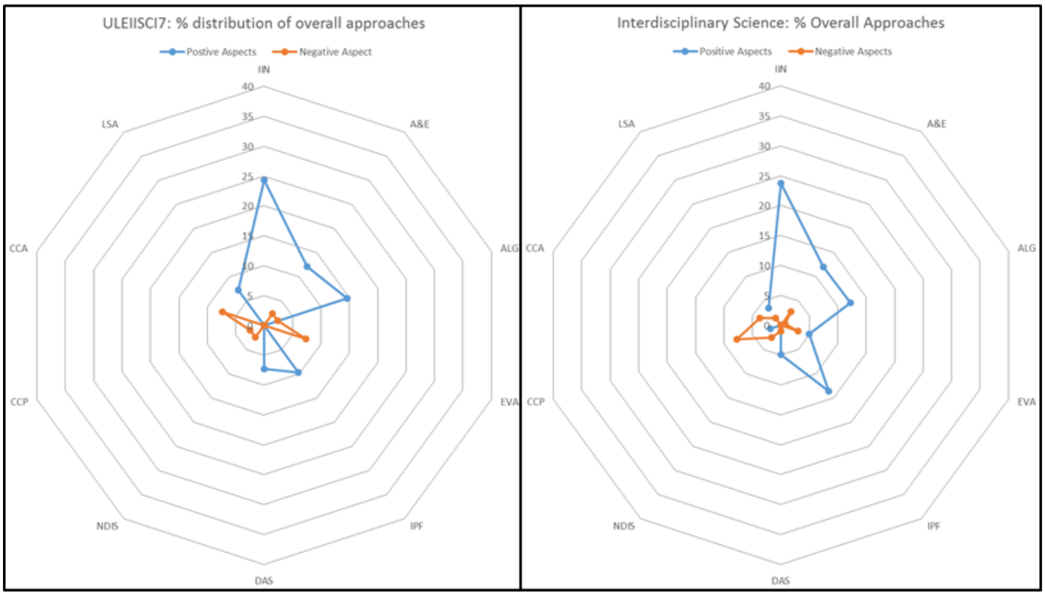

Figure 28 Radar charts displaying the percentage distribution of each approach for each interdisciplinary science undergraduate participant ULEISCI7 and as an entire discipline.

Figure 28 and Figure 29 shows that there is a lot of commonality between participants and their discipline profile. All participants show an elongation along the IPF+, IIN+ and ALG+. However, when we look at the negative codes participant ULEIISCI3 looks very different from the others, with greater elongation along the NDIS- code and truncation CCP/CCA- codes. The truncation of the CCP/CCA- code suggest that the participant was more confident with their ability to answer the problem and how to answer the problem. However, the participant did demonstrate an increase in becoming distracted by the context of the question.

For Interdisciplinary science participants problem one was answer in three different ways a) number of toilet uses per person, b) guess suitable ratio of people to toilets c) estimate the load capacity of the toilet and amount of effluence produced by a person.

The second problem was answered in four different ways; a) assumption that one revolution of the tyre would be sufficient, b) friction coefficient of tyre and road, c) number of atoms in one layer of a tyre and d) rate of degradation over lifetime of a tyre.

The third problem was answered in three different ways these were a) calculating the volume of the atmosphere and multiply by the density, b) calculate the number of molecules/ particles of ‘gas’ and c) using the equation $PV = nRT$.

4.3.6 Pharmacy Undergraduate students

Table 19 shows the quantified codes for the pharmacy undergraduates and the three most prominent codes were:

IPF+ The participant reflects on what is being asked in the problem. (18.94%)

IIN+ The participant identified a specific piece of information they think they need. (14.49%)

NDIS- The student becomes distracted by context. (9.61%)

The lowest frequency codes for pharmacy undergraduates were:

IPF- The participant does not reflect on the problem creating uncertainty in how to proceed. (0.13%)

CC+ The participant is confident. (0.65%)

NDIS+ The participant does not become distracted by context. (1.04%)

Figure 30, Figure 31 and Figure 32 presents the data in Table 19 in a series of radar charts

Table 19 Pharmacy results showing individual counts and percentage distribution of each code

Participants	UMONPHAR1		UMONPHAR2		UMONPHAR3		UMONPHAR4		UMONPHAR5		UMONPHAR6	
Codes	*N=*	*%*	*N=*	*%*	*N=*	*%*	*N=*	*%*	*N=*	*%*	*N=*	*%*
IIN+	15	23.08	17	27.87	10	15.87	0	0	7	10.77	7	10.61
A&E+	6	9.23	0	0	0	0	0	0	1	1.54	0	0
ALG+	8	12.31	0	0	4	6.36	0	0	3	4.62	8	12.12
EVA+	2	3.08	0	0	2	3.17	0	0	3	4.62	1	1.51
IPF+	12	18.46	10	16.39	10	15.87	5	15.15	12	18.44	15	22.73
DAS+	3	4.61	1	1.64	1	1.59	0	0	3	4.62	2	3.03
NDIS+	2	3.08	0	0	0	0	0	0	0	0	0	0
LSA+	3	4.61	0	0	0	0	0	0	0	0	2	3.03
IIN-	0	0	0	0	0	0	3	9.09	0	0	0	0
A&E-	0	0	3	4.92	5	7.95	6	18.19	4	6.15	6	9.09
ALG-	0	0	3	4.92	2	3.17	3	9.09	1	1.54	0	0
EVA-	2	3.08	3	4.92	3	4.76	4	12.12	7	10.77	3	4.55
IPF-	0	0	0	0	0	0	0	0	0	0	0	0
DAS-	0	0	3	4.92	2	3.17	3	9.09	1	1.54	2	3.03
NDIS-	2	3.08	8	13.11	10	15.87	3	9.09	8	12.31	9	13.64
LSA-	0	0	3	4.92	3	4.76	3	9.09	3	4.62	1	1.51
CC+	0	0	0	0	0	0	3	9.09	0	0	0	0
CCP-	7	10.77	8	13.11	8	12.70	0	0	11	16.92	9	13.64
CCA-	3	4.61	2	3.28	3	4.76	0	0	1	1.54	1	1.51

Participants	UMONPHAR7		UMONPHAR8		UMONPHAR9		UMONPHAR10		UMONPHAR11		UMONPHAR12	
Codes	*N=*	*%*	*N=*	*%*	*N=*	*%*	*N=*	*%*	*N=*	*%*	*N=*	*%*
IIN+	6	16.67	2	5.71	8	14.55	8	15.09	3	7.32	14	17.50
A&E+	2	5.56	2	5.71	2	3.64	2	3.77	2	4.88	10	12.50
ALG+	3	8.33	5	14.29	4	7.27	6	11.32	3	7.32	8	10
EVA+	0	0	0	0	1	1.82	2	3.77	2	4.88	9	11.25
IPF+	6	16.67	5	14.29	11	20	9	16.99	7	17.05	17	21.25
DAS+	2	5.56	0	0	3	5.45	3	5.66	3	7.32	3	3.75
NDIS+	2	5.56	1	2.86	0	0	0	0	1	2.44	2	2.5
LSA+	1	2.78	0	0	0	0	2	3.77	2	4.88	3	3.75
IIN-	0	0	2	5.71	0	0	0	0	1	2.44	0	0
A&E-	2	5.56	3	8.57	3	5.45	4	7.55	2	4.88	4	5
ALG-	1	2.77	1	2.86	0	0	1	1.89	1	2.44	0	0
EVA-	3	8.33	3	8.57	3	5.45	2	3.77	4	9.76	1	1.25
IPF-	0	0	1	2.86	0	0	0	0	0	0	0	0
DAS-	1	2.77	3	8.57	0	0	0	0	0	0	0	0
NDIS-	1	2.77	0	0	6	10.91	4	7.55	3	7.32	1	1.25
LSA-	2	5.56	3	8.57	3	5.45	1	1.89	1	2.44	0	0
CC+	0	0	0	0	0	0	0	0	0	0	0	0
CCP-	4	11.11	4	11.43	10	18.19	5	9.43	6	14.63	7	8.75
CCA-	0	0	0	0	1	1.82	4	7.55	0	0	1	1.25

Participants	UMONPHAR13		UMONPHAR14		Pharmacy Overall	
Codes	*N=*	*%*	*N=*	*%*	*N=*	*%*
IIN+	18	23.38	0	0	115	14.94
A&E+	0	0	0	0	27	3.51
ALG+	2	2.60	0	0	54	7.01
EVA+	0	0	0	0	22	2.86
IPF+	20	25.95	7	17.50	146	18.94
DAS+	0	0	0	0	24	3.12
NDIS+	0	0	0	0	8	1.04
LSA+	2	2.60	0	0	15	1.95
IIN-	0	0	3	7.50	9	1.17
A&E-	3	3.90	4	10	49	6.36
ALG-	2	2.60	6	15	21	2.73
EVA-	3	3.90	3	7.50	44	5.71
IPF-	0	0	0	0	1	0.13
DAS-	3	3.90	3	7.50	21	2.73
NDIS-	13	16.88	6	15	74	9.61
LSA-	1	1.30	3	7.50	27	3.51
CC+	0	0	2	5	5	0.65
CCP-	10	12.99	2	5	91	11.82
CCA-	0	0	1	2.50	17	2.21

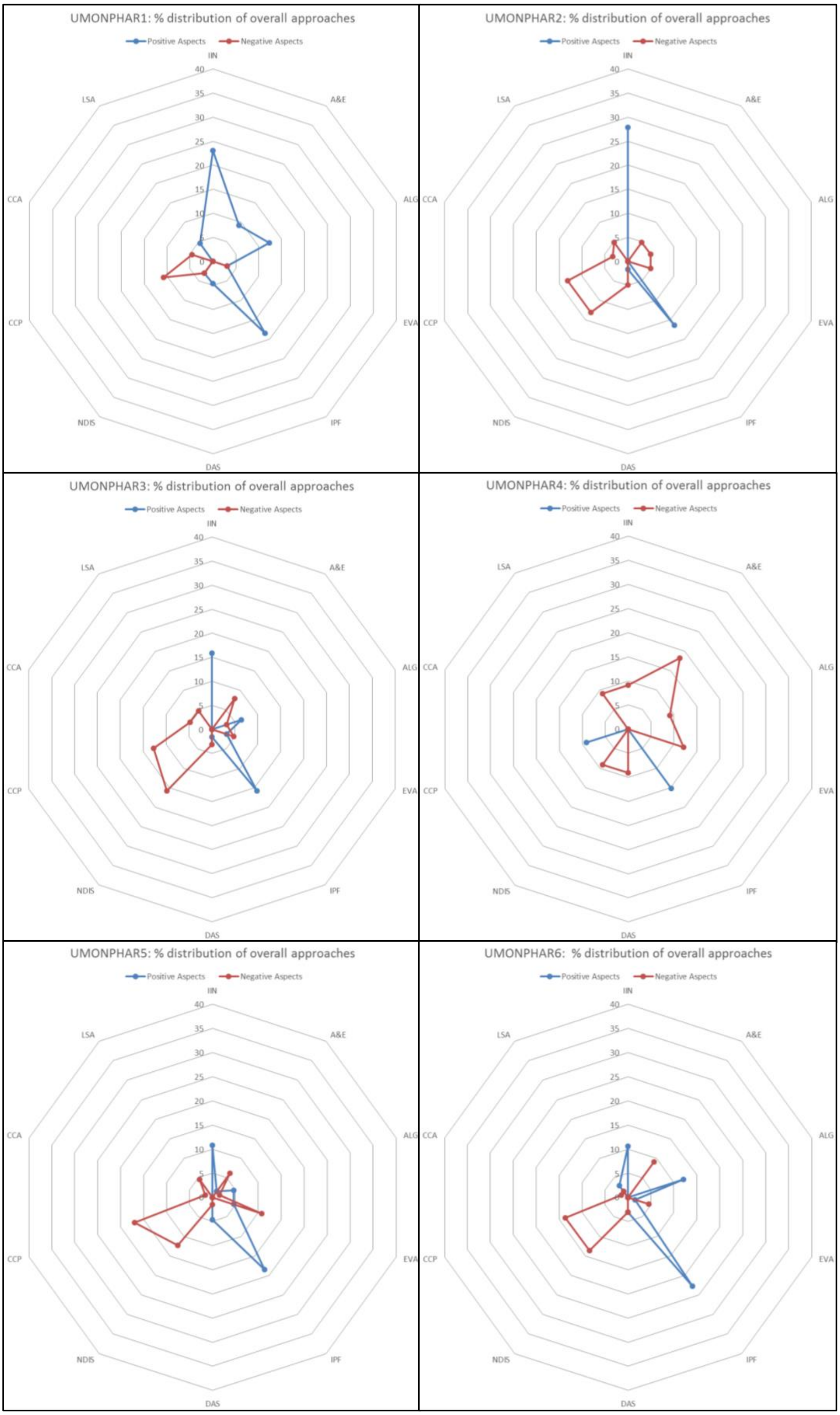

Figure 29 Radar charts displaying the percentage distribution of each approach for each pharmacy undergraduate participants UMONPHAR1 to UMONPHAR6

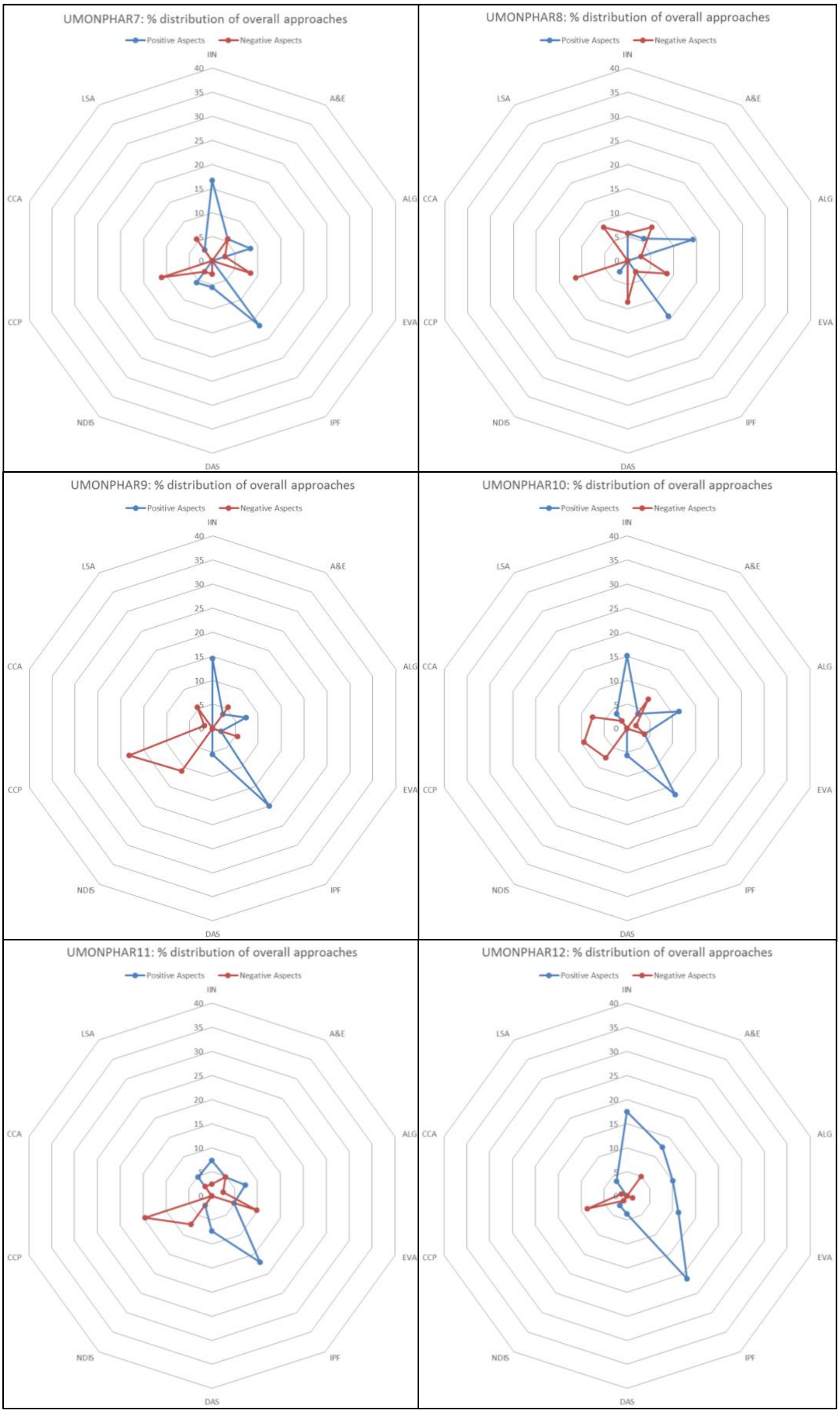

Figure 30 Radar charts displaying the percentage distribution of each approach for each pharmacy undergraduate participants UMONPHAR7 to UMONPHAR12

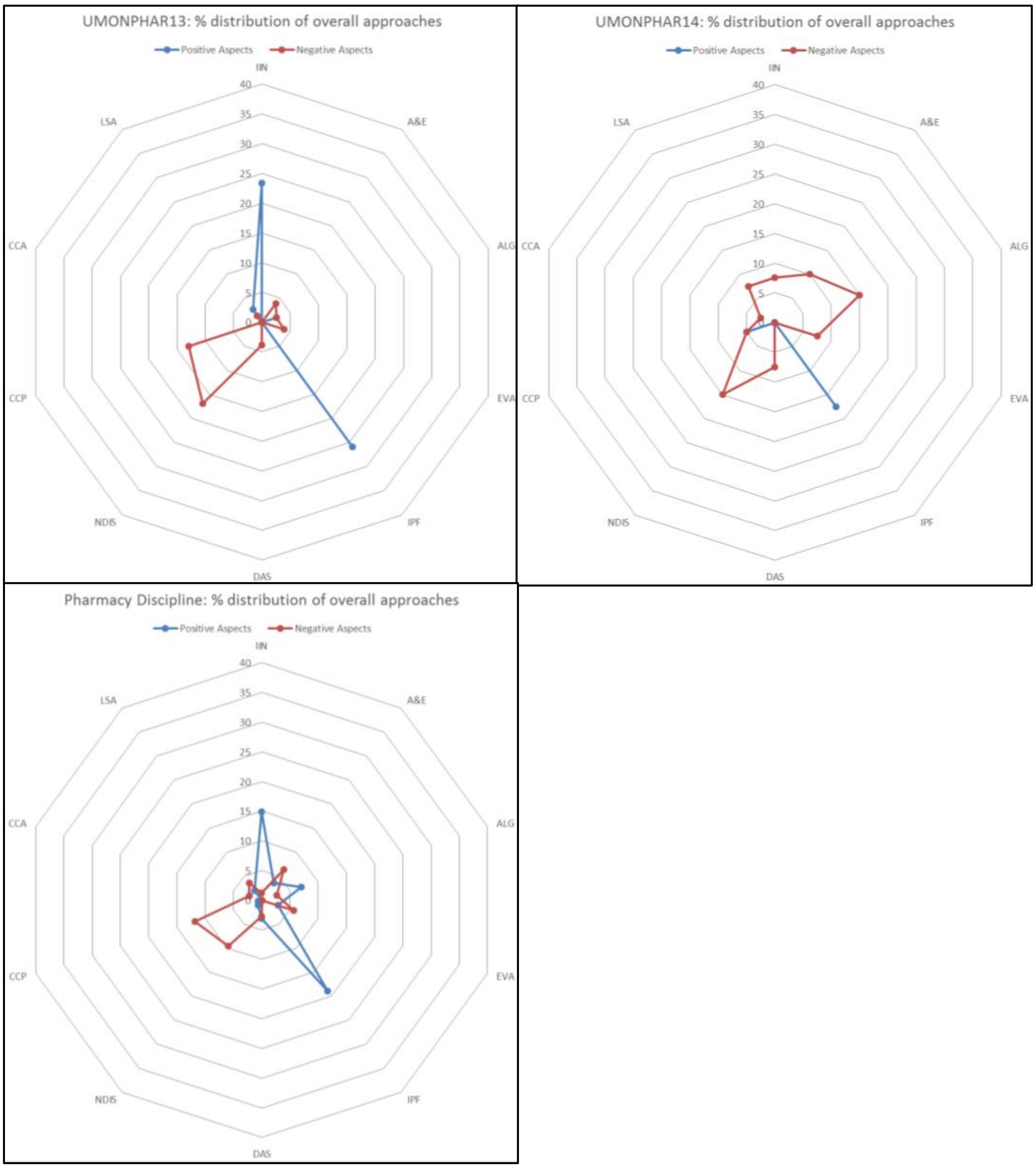

Figure 31 Radar charts displaying the percentage distribution of each approach for each pharmacy undergraduate participants UMONPHAR13, UMONPHAR14 and as an entire discipline.

Figure 30, Figure 31 and Figure 32 show that pharmacy undergraduates show some commonality with IPF+ consistently emerging as the prominent code. However, participants UMONPHAR4 and UMONPHAR14 asked for no information nor identified specific pieces of information that they thought they would require (IIN+), both with 0%. What is of interest is that both these participants were able to frame and identify the problem. This would suggest that both these participants knew what the problem was asking but were unable to identify the information required to implement their plan. Of further interest is the NDIS- (becoming distracted by the context) code emerging in a majority of participants. This has previously not been observed in the other disciplines and suggests that participants struggled to work with their strategy when immersed in the specifics of the context. Figure 30, Figure 31 and Figure 32 additionally show that pharmacy participants lack confidence and become confused with the problem (CCP-)

Problem 1 was answered in three ways a) by developing a template from a previous experience and applying it to this problem b) guessing a suitable ratio of people to toilets and c) outright guess at an answer

Problem 2 was answered in four ways a) rate of sweat produced multiplied by its density (assumed the same as water) b) metabolic rate c) developing a template from a previous experience and d) estimating loss based on water consumption

Problem 3 was answered in three different ways a) assumption based on heart rate b) rate of breath per minute and c) outright guess.

4.3.7 Chemistry Academic Participants

Table 20 shows the quantified codes for academics and the three most prominent codes are:

IIN+ The participant identified a specific piece of information they think they need. (18.79%)

CCP- The participant becomes confused with how to tackle the problem. (10.50%)

ALG+ The participant uses calculations and/or equations to solve the problem. (10.22%)

The lowest frequency codes for academics are:

> IPF- The participant does not reflect on the problem creating uncertainty in how to proceed. (0.28%)
>
> DAS- The participant does not develop a clear strategy. (0.28%)
>
> LSA- The participant employs an illogical strategy, with little grounding in scientific reasoning. (0.28%)

Figure 33 and Figure 34 presents the data in Table 20 in a series of radar charts

Table 20 Academic results showing individual counts and percentage distribution of each code

Participants	EXST1		EXST2		EXST3		EXST4		EXST5		EXST6	
Codes	*N=*	*%*	*N=*	*%*	*N=*	*%*	*N=*	*%*	*N=*	*%*	*N=*	*%*
IIN+	10	19.24	4	8.00	13	30.98	9	23.69	7	14.89	8	20.00
A&E+	3	5.77	4	8.00	3	7.14	5	13.17	4	8.51	5	12.50
ALG+	9	17.31	4	8.00	2	4.76	1	2.63	4	8.51	8	20.00
EVA+	8	15.38	3	6.00	2	4.76	1	2.63	5	10.64	3	7.50
IPF+	8	15.38	6	12.00	3	7.14	5	13.17	4	8.51	2	5.00
DAS+	3	5.77	2	4.00	3	7.14	3	7.89	3	6.38	3	7.50
NDIS+	3	5.77	3	6.00	1	2.38	3	7.89	2	4.26	1	2.50
LSA+	2	3.85	3	6.00	2	4.76	3	7.89	3	6.38	3	7.50
IIN-	0	0.00	2	4.00	1	2.38	0	0.00	0	0.00	0	0.00
A&E-	1	1.92	2	4.00	1	2.38	1	2.63	0	0.00	1	2.50
ALG-	0	0.00	2	4.00	1	2.38	2	5.26	1	2.13	0	0.00
EVA-	0	0.00	2	4.00	2	4.76	2	5.26	0	0.00	1	2.50
IPF-	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
DAS-	0	0.00	1	2.00	0	0.00	0	0.00	0	0.00	0	0.00
NDIS-	0	0.00	0	0.00	2	4.76	0	0.00	1	2.13	2	5.00
LSA-	1	1.92	0	0.00	1	2.38	0	0.00	0	0.00	0	0.00
CC+	1	1.92	0	0.00	1	2.38	3	7.89	1	2.13	3	7.50
CCP-	3	5.77	11	22.00	3	7.14	0	0.00	7	14.89	0	0.00
CCA-	0	0.00	1	2.00	1	2.38	0	0.00	5	10.64	0	0.00

Participants	EXST7		EXST8		Academic Overall	
Codes	*N=*	*%*	*N=*	*%*	*N=*	*%*
IIN+	18	18.95	12	30.00	68	18.79
A&E+	11	11.58	1	2.50	33	9.12
ALG+	8	8.42	3	7.50	37	10.22
EVA+	11	11.58	1	2.50	32	8.84
IPF+	8	8.42	2	5.00	35	9.67
DAS+	5	5.26	4	10.00	23	6.35
NDIS+	2	2.11	1	2.50	15	4.14
LSA+	3	3.16	3	7.50	20	5.52
IIN-	0	0.00	0	0.00	2	0.55
A&E-	0	0.00	2	5.00	7	1.93
ALG-	0	0.00	2	5.00	7	1.93
EVA-	0	0.00	2	5.00	7	1.93
IPF-	0	0.00	1	2.50	1	0.28
DAS-	0	0.00	0	0.00	1	0.28
NDIS-	5	5.26	3	7.50	11	3.04
LSA-	0	0.00	0	0.00	1	0.28
CC+	0	0.00	2	5.00	10	2.76
CCP-	16	16.84	1	2.50	38	10.50
CCA-	8	8.42	0	0.00	14	3.87

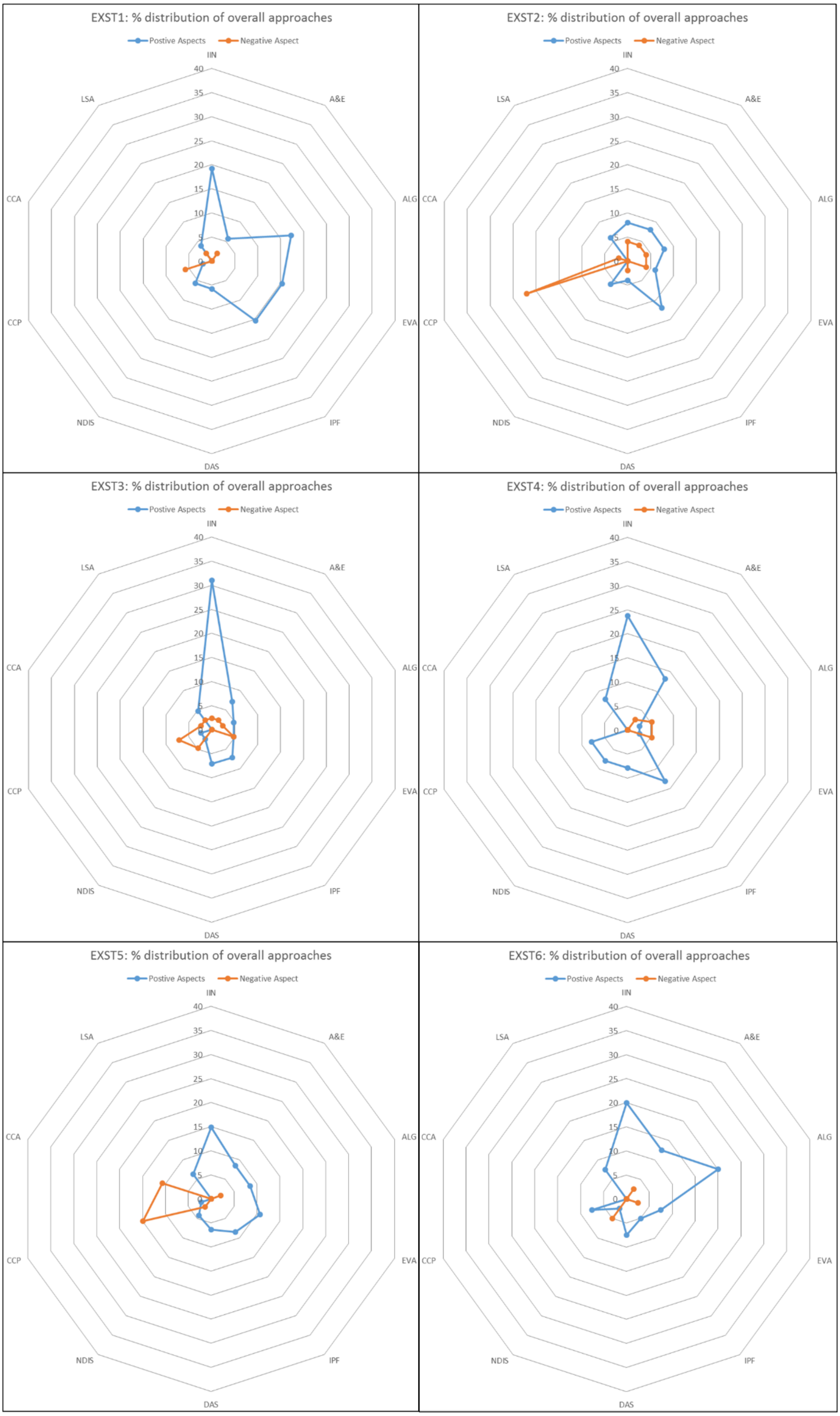

Figure 32 Radar charts displaying the percentage distribution of each approach for expert participants EXST1 to EXST6.

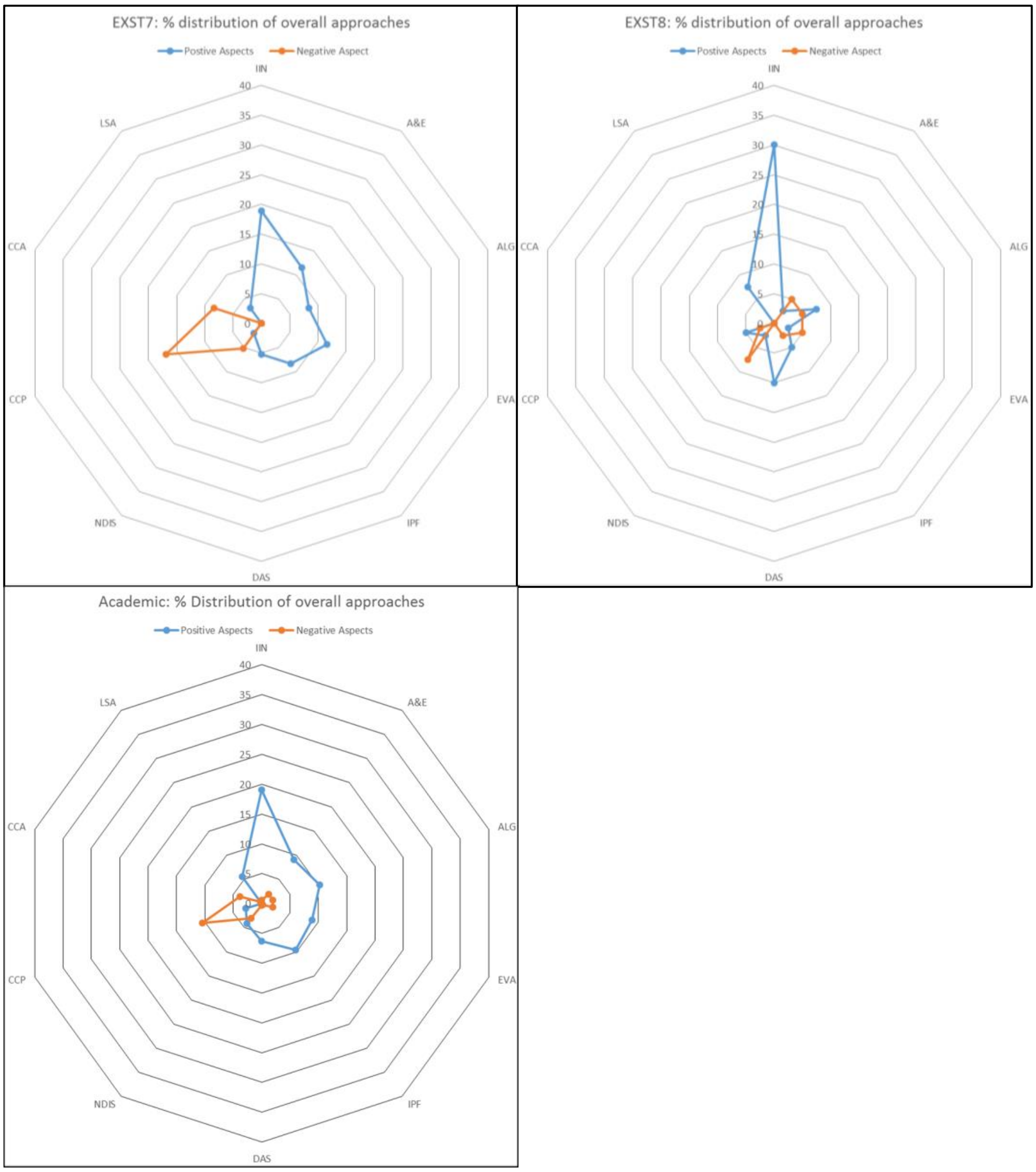

Figure 33 Radar charts displaying the percentage distribution of each approach for expert participants EXST7 to EXST8 and overall percentage for participant approaches

Figure 33 and Figure 34 shows that there is great diversity within the academic cohort, with three participants (EXST1, EXST5 and EXST7) having similar radar charts to that of the discipline overall chart. The main aspect in common that the academic participants had was that their codes were predominantly positive ones, with few negative codes present. What is beginning to emerge in academic participants is a greater percentage of approaches spent on evaluation as demonstrated in participants EXST1, EXST5, EXST6 and EXST7.

Question 1 was answered using three different strategies. These were: a) volume of waste produced by a person, b) guessing a ratio of people to toilets and c) number of visits to the toilet/ time spent on the toilet

Question 2 was answered using four different strategies. These were: a) how many atoms are on the surface area of a tyre, b) assumption that one revolution of a tyre would be sufficient, c) rate of degradation over the lifetime of a tyre and d) guessing at the speed of tyre and number of revolutions

Question 3 was answered using four different strategies. These were, a) volume of a molecule of O_2 and N_2 multiplied by the mass of each molecule, b) volume of the Earth's atmosphere multiplied by the density, c) number of moles of gas in the atmosphere and d) surface area of the Earth multiplied by the pressure

4.3.8 Industrialist Participants

Table 21 shows the quantified codes for industrialists and the three most prominent codes are:

IIN+ The participant identified a specific piece of information they think they need. (20.70%)

IPF+ The participant reflects on what is being asked in the problem. (17.67%)

ALG+ The participant uses calculations and/or equations to solve the problem. (14.88%)

The lowest frequency codes for are:

IIN- The participant fails to identify a specific piece of information they need. (0.00%)

IPF- The participant does not reflect on the problem creating uncertainty in how to proceed. (0.00%)

DAS- The participant does not develop a clear strategy. (0.47%)

LSA- The participant employs an illogical strategy, with little grounding in scientific reasoning. (0.47%)

Figure 35 and Figure 36 presents the data in Table 21 in a series of radar charts.

Table 21 Industrialist results showing individual counts and percentage distribution of each code

Participants	EXST9		EXST10		EXST11		EXST12		EXST13		EXST14	
Codes	*N=*	*%*	*N=*	*%*	*N=*	*%*	*N=*	*%*	*N=*	*%*	*N=*	*%*
IIN+	18	24.99	10	19.23	10	18.87	13	14.29	23	28.03	15	18.75
A&E+	6	8.33	4	7.69	3	5.66	6	6.59	0	0.00	7	8.75
ALG+	8	11.11	8	15.38	7	13.21	19	20.86	8	9.76	14	17.50
EVA+	6	8.33	3	5.77	2	3.77	9	9.89	3	3.66	4	5.00
IPF+	11	15.28	7	13.46	10	18.87	11	12.09	20	24.39	17	21.25
DAS+	3	4.17	3	5.77	3	5.66	3	3.30	1	1.22	3	3.75
NDIS+	1	1.39	0	0.00	1	1.89	4	4.40	5	6.10	0	0.00
LSA+	3	4.17	2	3.85	3	5.66	3	3.30	3	3.66	2	2.50
IIN-	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
A&E-	0	0.00	0	0.00	1	1.89	1	1.10	3	3.66	0	0.00
ALG-	1	1.39	2	3.85	0	0.00	0	0.00	2	2.44	0	0.00
EVA-	0	0.00	2	3.85	2	3.77	0	0.00	2	2.44	1	1.25
IPF-	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
DAS-	0	0.00	0	0.00	0	0.00	0	0.00	2	2.44	0	0.00
NDIS-	2	2.78	3	5.77	2	3.77	1	1.10	1	1.22	3	3.75
LSA-	0	0.00	1	1.92	0	0.00	0	0.00	0	0.00	1	1.25
CC+	0	0.00	2	3.85	0	0.00	0	0.00	1	1.22	1	1.25
CCP-	4	5.56	4	7.69	8	15.09	13	14.29	3	3.66	7	8.75
CCA-	9	12.50	1	1.92	1	1.89	8	8.79	5	6.10	5	6.25

Participants	Industrialist Overall	
Codes	*N=*	*%*
IIN+	89	20.70
A&E+	26	6.05
ALG+	64	14.88
EVA+	27	6.28
IPF+	76	17.67
DAS+	16	3.72
NDIS+	11	2.56
LSA+	16	3.72
IIN-	0	0.00
A&E-	5	1.16
ALG-	5	1.16
EVA-	7	1.63
IPF-	0	0.00
DAS-	2	0.47
NDIS-	12	2.79
LSA-	2	0.47
CC+	4	0.93
CCP-	39	9.07
CCA-	29	6.74

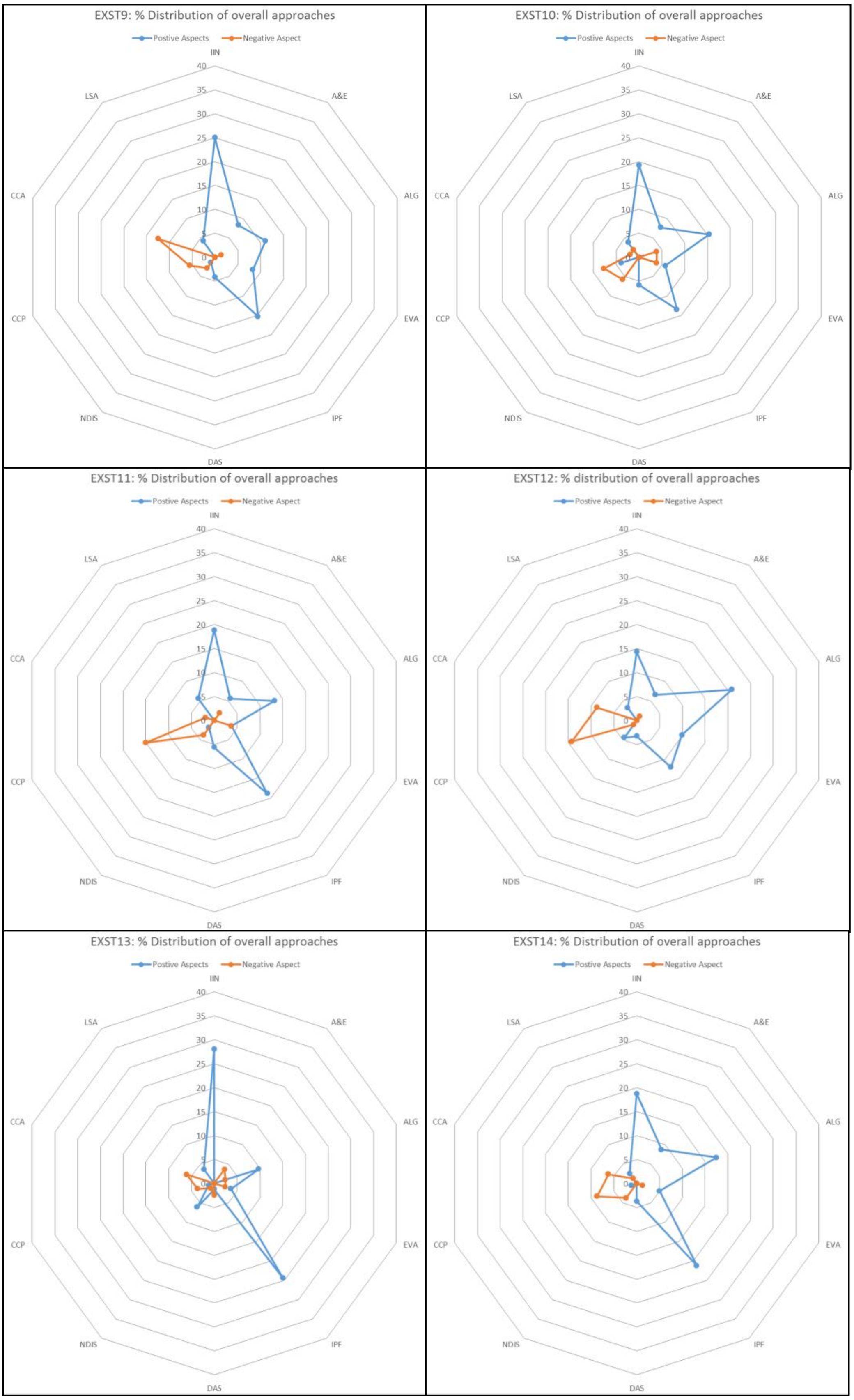

Figure 34 Radar charts displaying the percentage distribution of each approach for expert participants EXST9 to EXST14.

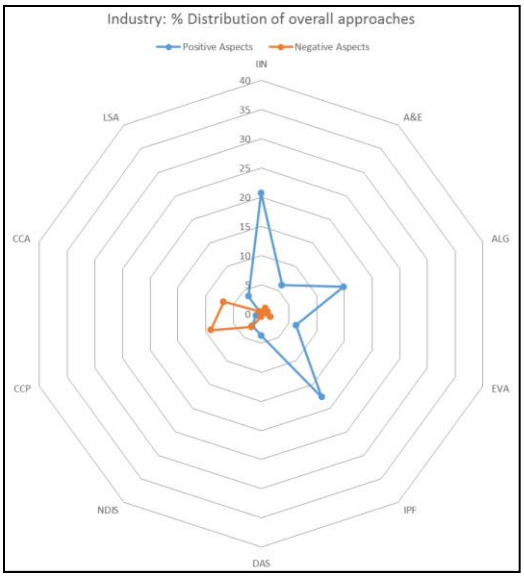

Figure 35 Overall percentage distribution for participant approaches

Figure 35 and Figure 36 show a very similar shaped profile across all participants with extensions along the IIN+, ALG+ and the IPF+. All the radar charts for each participant look very similar to those shown in section 4.3.1 for the chemistry participants. This similarity would suggest that the approaches used by industrialists are different from the academics, but very similar to those approaches used by chemistry undergraduate participants. The industrialists show predominantly positive codes, with the main negative codes shown for CCP/CCA.

Problem 1 was answered in 4 different ways a) time spent in the toilets b) guessing ratio of people to toilets c) number of visits per person and d) lack of information so no answer provided.

Problem 2 was answered in 4 different ways a) rate of ware on the tyre (by experimentation) b) assumption of one rotation c) rate of wear of the lifetime of a tyre and d) lack of information so no answer provided.

Problem 3 was answered in 2 different ways a) volume of a shell multiplied by the density of the atmosphere and b) the number of moles of gas in the atmosphere.

4.3.9 Postgraduate Students

Table 22 shows the quantified codes for the postgraduate students and the three highest frequency codes are:

ALG+ The participant uses calculations and/or equations to solve the problem. (19.78%)

IIN+ The participant identified a specific piece of information they think they need. (15.45%)

IPF+ The participant reflects on what is being asked in the problem. (14.63%)

The lowest frequency codes for postgraduate students are:

DAS- The participant does not develop a clear strategy. (0.00%)

IPF- The participant does not reflect on the problem creating uncertainty in how to proceed. (0.54%)

IIN- The participant fails to identify a specific piece of information they need. (0.54%)

Figure 37 presents the data in Table 22 in a series of radar charts.

Table 22 Postgraduate results showing individual counts and percentage distribution of each code

Participants	PGHULL1		PGHULL2		PGHULL3		PGHULL4		PGHULL5		Postgraduates Overall	
Codes	*N=*	*%*	*N=*	*%*	*N=*	*%*	*N=*	*%*	*N=*	*%*	*N=*	*%*
IIN+	12	27.88	8	9.41	20	27.77	11	12.22	6	7.69	57	15.49
A&E+	2	4.65	16	18.82	5	6.94	19	21.12	9	11.54	51	13.86
ALG+	5	11.63	21	24.70	9	12.50	15	16.67	23	30.00	73	19.86
EVA+	1	2.33	2	2.35	3	4.17	3	3.33	5	6.41	14	3.80
IPF+	4	9.30	5	5.88	14	19.44	19	21.11	12	15.38	54	14.67
DAS+	3	6.98	4	4.71	3	4.17	3	3.33	3	3.85	16	4.35
NDIS+	3	6.98	1	1.18	1	1.39	5	5.56	1	1.28	11	2.99
LSA+	2	4.65	1	1.18	3	4.17	3	3.33	2	2.56	11	2.99
IIN-	0	0.00	0	0.00	0	0.00	1	1.11	1	1.28	2	0.54
A&E-	1	2.33	3	3.53	2	2.78	0	0.00	0	0.00	6	1.63
ALG-	1	2.33	0	0.00	1	1.39	0	0.00	0	0.00	2	0.54
EVA-	2	4.65	3	3.53	1	1.39	1	1.11	1	1.28	8	2.17
IPF-	1	2.33	1	1.18	0	0.00	0	0.00	0	0.00	2	0.54
DAS-	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
NDIS-	0	0.00	2	2.35	2	2.78	1	1.11	2	2.56	7	1.90
LSA-	1	2.33	2	2.35	0	0	0	0	1	1.28	5	1.09
CC+	1	2.33	0	0	0	0	0	0	0	0	1	0.27
CCP-	2	4.65	12	14.12	5	6.94	7	7.78	9	11.54	35	9.51
CCA-	2	4.65	4	4.71	3	4.17	2	2.22	3	3.85	14	3.80

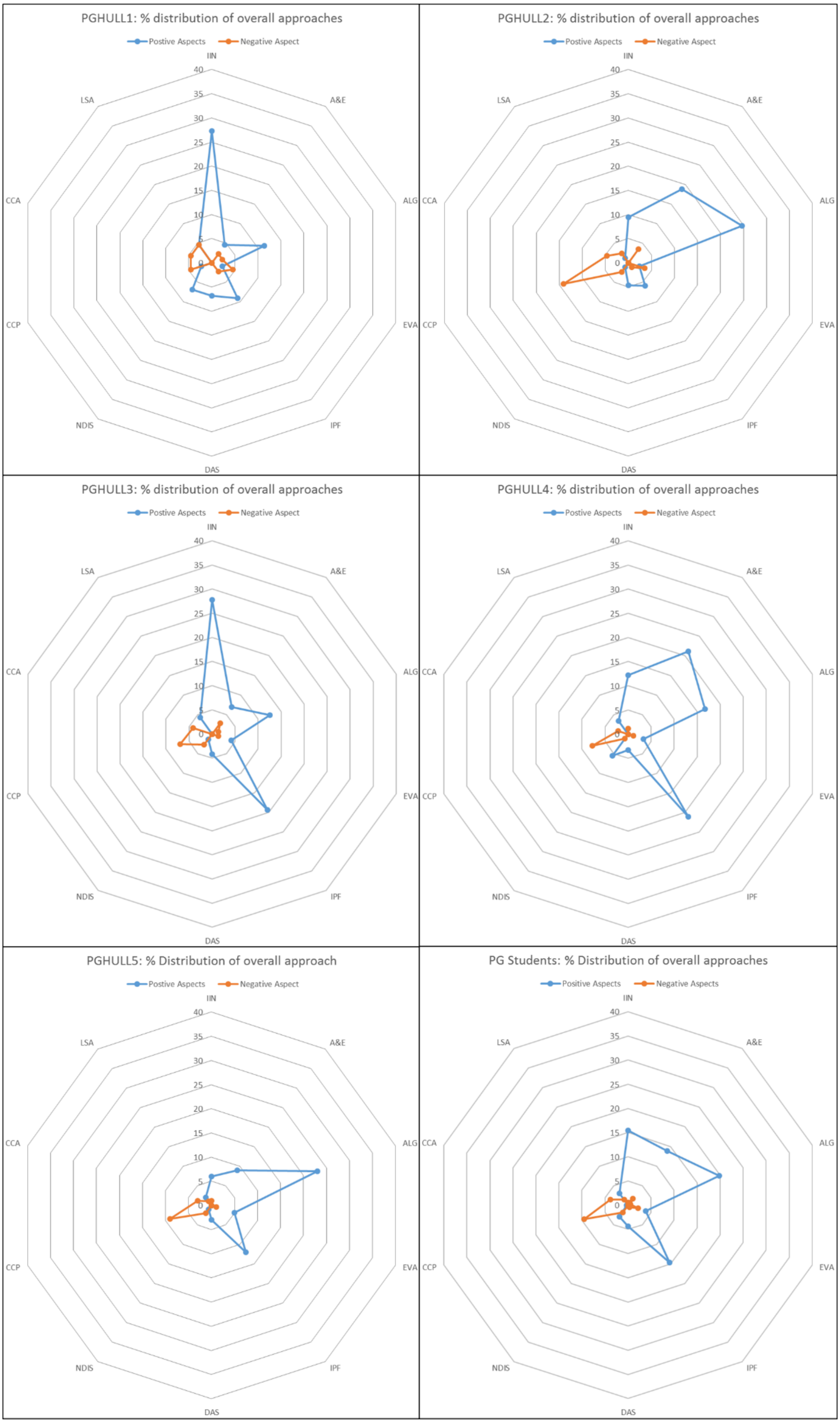

Figure 36 Radar charts displaying the percentage distribution of each approach for participants PGHULL1 to PGHULL5, and overall percentage distribution for participant approaches

Figure 37 shows that postgraduate students have some similarities, with all participants showing a prominence towards either IIN+ or A&E+, and where one was prominent the other was not. This would suggest that some postgraduates would rather make approximations and estimations instead of asking for specific information, with some participants still preferring to ask for information without making their own approximations and estimations. All postgraduate participants showed a prominence towards ALG+ which would suggest that these participants employ equations and calculations in their strategy. Few participants showed any lack of confidence or confusion with their ability to solve problems (CCA-), but did show that they did become confused with stages in the problem (CCP-)

Problem 1 was answered in 3 different ways a) estimate ratio of people to toilets b) frequency of visits to the toilet and c) duration of use of the toilet

Problem 2 was answered in 3 different ways a) assumption one revolution would be sufficient b) rate of ware over time based on surface area and c) proportional ware based on lifetime of the tyre

Problem 3 was answered in 2 different ways a) geometric shell calculation multiplied by density and b) number of moles of gas in the atmosphere.

Considering there are only five participants in the postgraduate study there are a wide variety of approaches used when answering these problems, in particular problem 1, which held three different strategies to answer the problem.

4.3.10 Academic Group Participants.

Table 23 shows the quantified codes for the groups of academics and shows that the three highest frequency codes are:

> ALG+ The participant uses calculations and/or equations to solve the problem. (18.53%)
>
> IPF+ The participant reflects on what is being asked in the problem. (17.72%)
>
> IIN+ The participant identified a specific piece of information they think they need. (12.96%)

The lowest frequency codes for the groups were harder to determine because many themes did not emerge and so it would be inappropriate to assign any of the codes as the lowest frequency. Figure 38 and Figure 39 are radar charts which represent the data presented in Table 23.

Table 23 Academic group results showing individual counts and percentage distribution of each code

Participants	EPHYSGP1		EPHYSGP2		ECHEMGP1		ECHEMGP2		ECHEMGP3		EMIXGP1	
Codes	*N=*	*%*	*N=*	*%*	*N=*	*%*	*N=*	*%*	*N=*	*%*	*N=*	*%*
IIN+	3	5.77	10	13.33	11	18.97	9	13.64	8	12.31	VOID	VOID
A&E+	6	11.54	5	6.67	7	12.07	9	13.64	7	10.77	VOID	VOID
ALG+	10	19.22	13	17.33	9	15.52	11	16.64	12	18.46	VOID	VOID
EVA+	6	11.54	5	6.67	4	6.90	8	12.12	6	9.23	VOID	VOID
IPF+	9	17.31	11	14.67	14	24.12	10	15.15	14	21.54	VOID	VOID
DAS+	2	3.85	3	4.00	3	5.17	4	6.06	4	6.15	VOID	VOID
NDIS+	2	3.85	1	1.33	0	0	1	1.52	0	0	VOID	VOID
LSA+	2	3.85	2	5.33	2	3.45	3	4.55	3	4.62	VOID	VOID
IIN-	0	0	0	0	0	0	0	0	0	0	VOID	VOID
A&E-	1	1.92	2	2.67	0	0	0	0	0	0	VOID	VOID
ALG-	0	0	0	0	0	0	0	0	0	0	VOID	VOID
EVA-	0	0	0	0	0	0	0	0	0	0	VOID	VOID
IPF-	0	0	0	0	0	0	0	0	0	0	VOID	VOID
DAS-	0	0	6	8	0	0	1	1.52	0	0	VOID	VOID
NDIS-	1	1.92	2	2.67	4	6.90	3	4.55	7	10.77	VOID	VOID
LSA-	0	0	0	0	0	0	0	0	0	0	VOID	VOID
CC+	0	0	0	0	0	0	0	0	0	0	VOID	VOID
CCP-	9	17.31	9	12.00	4	6.90	6	9.09	4	6.15	VOID	VOID
CCA-	1	1.92	4	5.33	0	0	1	1.52	0	0	VOID	VOID

Participants	EMIXGP2		Expert Groups Overall	
Codes	*N=*	*%*	*N=*	*%*
IIN+	8	12.90	49	12.96
A&E+	4	6.45	38	10.05
ALG+	15	24.19	70	18.53
EVA+	8	12.90	37	9.79
IPF+	9	14.52	67	17.72
DAS+	2	3.23	18	4.76
NDIS+	1	1.61	5	1.32
LSA+	2	3.23	16	4.23
IIN-	0	0	0	0
A&E-	1	1.61	4	1.06
ALG-	0	0	0	0
EVA-	0	0	0	0
IPF-	0	0	0	0
DAS-	0	0	7	1.85
NDIS-	2	3.23	19	5.03
LSA-	0	0	0	0
CC+	0	0	0	0
CCP-	7	11.29	39	10.32
CCA-	3	4.84	9	2.38

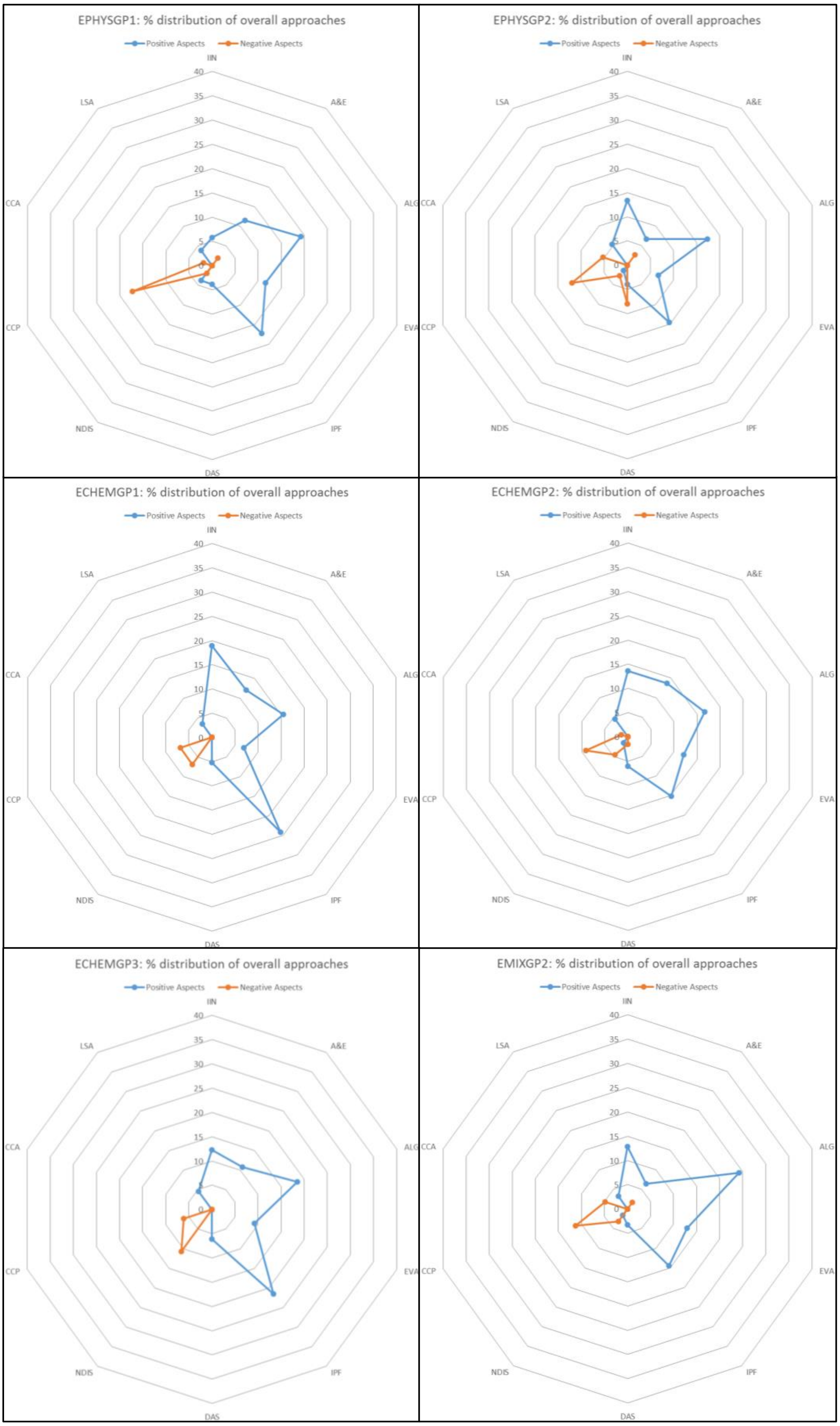

Figure 37 Radar charts displaying the percentage distribution of each approach for individual academic group participants

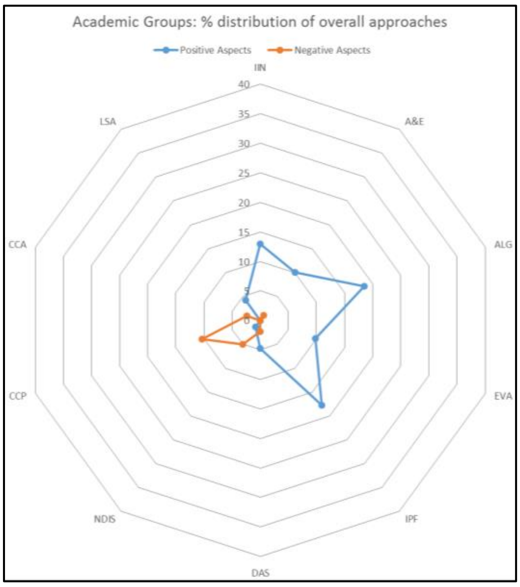

Figure 38 Radar chart displaying the percentage distribution of each approach for overall academic group participants

Figure 38 and Figure 39 show that academics working in groups show largely positive codes with all groups showing prominence towards ALG+ and IPF+. What is interesting is that groups of academics used less IIN+ and more A&E+ than when working independently. This would suggest that as a group they have the confidence to make estimations and approximations without requiring guidance. However, it may also suggest that participants in the group can call on a wider variety of expertise and therefore not need to ask for specific pieces of information. The overall profile in Figure 39 shows that academic experts show prominence towards IIN+, ALG+ and IPF+, with secondary emerging prominence towards A&E+ and EVA+. When compared against the overall profile for individual academics (Figure 34) the shape is very different, which would suggest that the approaches and strategies used in academic groups is different from when they work as individuals.

4.3.11 Primary and Secondary Cluster Analysis

Further analysis was carried out using a cluster based approach and was used to identify emerging differences between the groups. Cluster analysis is where codes holding similar percentage distribution are highlighted and grouped together and therefore identified as a cluster. In this study only primary and secondary clusters were required to identify differences between the participant groups. Table 24, Table 25 and Table 26 show the primary and secondary clusters for the overall discipline profiles for all discipline profiles.

Table 24 Primary and secondary cluster analysis for chemistry, physics and sports rehabilitation undergraduate students

	Chemistry Undergraduate Students				**Physics Undergraduate Students**				**Sports Rehabilitation Undergraduate Students**			
	Primary		**Secondary**		**Primary**		**Secondary**		**Primary**		**Secondary**	
Codes	*N=*	*%=*	*N=*	*%=*	*N=*	*%=*	*N=*	*%=*	*N=*	*%=*	*N=*	*%=*
IIN+	220	24.76	220	24.76	267	24.14	267	24.14	28	12.34	28	12.34
A&E+	66	7.23	66	7.23	112	10.21	112	10.21	19	8.37	19	8.37
ALG+	128	15.51	128	15.51	184	16.77	184	16.77	9	3.96	9	3.96
EVA+	33	3.67	33	3.67	42	3.83	42	3.83	3	1.32	3	1.32
IPF+	92	10.69	92	10.69	129	11.76	129	11.76	18	7.93	18	7.93
DAS+	45	5.14	45	5.14	58	5.29	58	5.29	11	4.85	11	4.85
NDIS+	1	0.42	1	0.42	24	2.19	24	2.19	16	7.05	16	7.05
LSA+	15	1.78	15	1.78	46	4.19	46	4.19	0	0.00	0	0.00
IIN-	3	0.31	3	0.31	0	0.00	0	0.00	6	2.64	6	2.64
A&E-	20	2.20	20	2.20	17	1.55	17	1.55	14	6.17	14	6.17
ALG-	9	0.94	9	0.94	3	0.27	3	0.27	13	5.73	13	5.73
EVA-	25	2.83	25	2.83	21	1.91	21	1.91	15	6.61	15	6.61
IPF-	1	0.10	1	0.10	3	0.27	3	0.27	5	2.20	5	2.20
DAS-	9	0.94	9	0.94	3	0.27	3	0.27	7	3.08	7	3.08
NDIS-	31	3.25	31	3.25	21	1.91	21	1.91	2	0.88	2	0.88
LSA-	31	3.35	31	3.35	5	0.46	5	0.46	18	7.93	18	7.93
CC+	10	1.26	10	1.26	7	0.64	7	0.64	5	2.20	5	2.20
CCP-	106	11.53	106	11.53	124	11.30	124	11.30	23	10.13	23	10.13
CCA-	39	4.09	39	4.09	31	2.83	31	2.83	15	6.61	15	6.61

Table 25 Primary and secondary cluster analysis for psychology, inter-disciplinary science and pharmacy undergraduate students

	Psychology Undergraduate Students				**Inter-disciplinary Science Undergraduate Students**				**Pharmacy Undergraduate Students**			
	Primary		**Secondary**		**Primary**		**Secondary**		**Primary**		**Secondary**	
Codes	*N=*	*%=*	*N=*	*%=*	*N=*	*%=*	*N=*	*%=*	*N=*	*%=*	*N=*	*%=*
IIN+	23	7.01	23	7.01	101	23.76	101	23.76	115	14.94	115	14.94
A&E+	27	8.23	27	8.23	51	12.00	51	12.00	27	3.51	27	3.51
ALG+	1	0.30	1	0.30	52	12.24	52	12.24	54	7.01	54	7.01
EVA+	2	0.61	2	0.61	21	4.94	21	4.94	22	2.86	22	2.86
IPF+	30	9.15	30	9.15	58	13.65	58	13.65	146	18.94	146	18.94
DAS+	14	4.27	14	4.27	21	4.94	21	4.94	24	3.12	24	3.12
NDIS+	15	4.57	15	4.57	0	0.00	0	0.00	8	1.04	8	1.04
LSA+	1	0.30	1	0.30	15	3.53	15	3.53	15	1.95	15	1.95
IIN-	15	4.57	15	4.57	0	0.00	0	0.00	9	1.17	9	1.17
A&E-	20	6.10	20	6.10	12	2.82	12	2.82	49	6.36	49	6.36
ALG-	26	7.93	26	7.93	3	0.71	3	0.71	21	2.73	21	2.73
EVA-	25	7.62	25	7.62	13	3.06	13	3.06	44	5.71	44	5.71
IPF-	11	3.35	11	3.35	0	0.00	0	0.00	1	0.13	1	0.13
DAS-	13	3.96	13	3.96	4	0.94	4	0.94	21	2.73	21	2.73
NDIS-	22	6.71	22	6.71	11	2.59	11	2.59	74	9.61	74	9.61
LSA-	26	7.93	26	7.93	6	1.41	6	1.41	27	3.51	27	3.51
CC+	10	3.05	10	3.05	8	1.88	8	1.88	5	0.65	5	0.65
CCP-	36	10.99	36	10.99	33	7.76	33	7.76	91	11.82	91	11.82
CCA-	11	3.35	11	3.35	16	3.76	16	3.76	17	2.21	17	2.21

Table 26 Primary and secondary cluster analysis for academic and industrialist participants, and chemistry postgraduate students

	Academic Participants				**Industrialist Participants**				**Chemistry Post Graduate Students**			
	Primary		**Secondary**		**Primary**		**Secondary**		**Primary**		**Secondary**	
Codes	*N=*	*%=*	*N=*	*%=*	*N=*	*%=*	*N=*	*%=*	*N=*	*%=*	*N=*	*%=*
IIN+	68	18.79	68	18.78	89	20.70	89	20.70	57	15.45	57	15.45
A&E+	33	9.12	33	9.12	26	6.05	26	6.05	51	13.82	51	13.82
ALG+	37	10.22	37	10.22	64	14.88	64	14.88	73	19.78	73	19.78
EVA+	32	8.84	32	8.84	27	6.28	27	6.28	14	3.79	14	3.79
IPF+	35	9.67	35	9.67	76	17.67	76	17.67	54	14.63	54	14.63
DAS+	23	6.35	23	6.35	16	3.72	16	3.72	16	4.34	16	4.34
NDIS+	15	4.14	15	4.14	11	2.56	11	2.56	11	2.98	11	2.98
LSA+	20	5.52	20	5.52	16	3.72	16	3.72	11	2.98	11	2.98
IIN-	2	0.55	2	0.55	0	0.00	0	0.00	2	0.54	2	0.54
A&E-	7	1.93	7	1.93	5	1.16	5	1.16	6	1.63	6	1.63
ALG-	7	1.93	7	1.93	5	1.16	5	1.16	2	0.54	2	0.54
EVA-	7	1.93	7	1.93	7	1.63	7	1.63	8	2.17	8	2.17
IPF-	1	0.28	1	0.28	0	0.00	0	0.00	2	0.54	2	0.54
DAS-	1	0.28	1	0.28	2	0.47	2	0.47	0	0.00	0	0.00
NDIS-	11	3.04	11	3.04	12	2.79	12	2.79	7	1.90	7	1.90
LSA-	1	0.28	1	0.28	2	0.47	2	0.47	5	1.36	5	1.36
CC+	10	2.76	10	2.76	4	0.93	4	0.93	1	0.27	1	0.27
CCP-	38	10.50	38	10.50	39	9.07	39	9.07	35	9.49	35	9.49
CCA-	14	3.87	14	3.87	29	6.74	29	6.74	14	3.79	14	3.79

4.4 Traffic Lighting Solutions

The data collected through the emergent qualitative coding was analysed was further analysed through the traffic lighting process described in section 2.8. Each participant's solution was individually traffic lighted. Each question from each participant was assigned a colour code, where a red box containing an R denotes a red solution, a yellow box with an A denoting an amber solution and a green box with a G denoting a green solution. Table 27 shows the traffic lighted solutions for each participant from every cohort.

Table 27 Traffic light scores for all individual participants

Participant	UHULLCH1			UHULLCH2			UHULLCH3			UHULLCH4		
Question	1	2	3	1	2	3	1	2	3	1	2	3
Traffic Light	R	R	G	A	R	A	A	R	R	A	A	A
Participant	UHULLCH5			UHULLCH6			UHULLCH7			UHULLCH8		
Question	1	2	3	1	2	3	1	2	3	1	2	3
Traffic Light	R	A	G	R	R	R	G	G	G	A	G	G
Participant	UHULLCH9			UHULLCH10			UHULLCH11			UHULLCH12		
Question	1	2	3	1	2	3	1	2	3	1	2	3
Traffic Light	G	A	A	G	A	G	A	A	A	R	A	A
Participant	USTRACH1			USTRACH2			USTRACH3			USTRACH4		
Question	1	2	3	1	2	3	1	2	3	1	2	3
Traffic Light	R	A	A	A	R	A	G	A	R	A	R	G
Participant	USTRACH5			UHULLPH1			UHULLPH2			UHULLPH3		
Question	1	2	3	1	2	3	1	2	3	1	2	3
Traffic Light	R	R	G	R	A	A	G	G	G	A	G	G
Participant	UHULLPH4			UHULLPH5			UHULLPH6			UHULLPH7		
Question	1	2	3	1	2	3	1	2	3	1	2	3
Traffic Light	R	R	G	R	R	A	A	R	G	A	A	R

Participant	UHULLPH8			UHULLPH9			UHULLPH10			UEDINPH1		
Question	1	2	3	1	2	3	1	2	3	1	2	3
Traffic Light	A	G	R	A	R	A	A	G	A	A	G	G
Participant	UEDINPH2			UEDINPH3			UEDINPH4			UEDINPH5		
Question	1	2	3	1	2	3	1	2	3	1	2	3
Traffic Light	R	G	G	G	G	A	A	A	A	A	G	G
Participant	UEDINPH6			UEDINPH7			UHULLSR1			UHULLSR2		
Question	1	2	3	1	2	3	1	2	3	1	2	3
Traffic Light	R	G	A	R	A	A	R	A	R	A	R	R
Participant	UHULLSR3			UHULLSR4			UHULLSR5			UHULLSR6		
Question	1	2	3	1	2	3	1	2	3	1	2	3
Traffic Light	R	A	R	R	A	R	R	A	R	R	A	R
Participant	UHULLPS1			UHULLPS2			UHULLPS3			UHULLPS4		
Question	1	2	3	1	2	3	1	2	3	1	2	3
Traffic Light	R	R	A	R	A	R	A	A	A	R	R	R
Participant	UHULLPS5			UHULLPS6			UHULLPS7			UHULLPS8		
Question	1	2	3	1	2	3	1	2	3	1	2	3
Traffic Light	R	R	R	R	R	R	R	R	R	R	R	R
Participant	UHULLPS9			ULEIISCI1			ULEIISCI2			ULEIISCI3		
Question	1	2	3	1	2	3	1	2	3	1	2	3
Traffic Light	R	R	R	R	G	G	A	G	G	R	R	R
Participant	ULEIISCI4			ULEIISCI5			ULEIISCI6			ULEIISCI7		
Question	1	2	3	1	2	3	1	2	3	1	2	3
Traffic Light	A	A	A	G	A	A	R	A	A	G	A	A
Participant	UMONPHAR1			UMONPHAR2			UMONPHAR3			UMONPHAR4		
Question	1	2	3	1	2	3	1	2	3	1	2	3
Traffic Light	G	G	R	R	R	R	R	R	R	A	R	R
Participant	UMONPHAR5			UMONPHAR6			UMONPHAR7			UMONPHAR8		
Question	1	2	3	1	2	3	1	2	3	1	2	3
Traffic Light	R	R	R	R	R	R	R	A	R	R	R	R

Participant	UMONPHAR9			UMONPHAR10			UMONPHAR11			UMONPHAR12		
Question	1	2	3	1	2	3	1	2	3	1	2	3
Traffic Light	A	R	R	R	G	R	A	R	R	A	A	G
Participant	UMONPHAR13			UMONPHAR14			EXST1			EXST2		
Question	1	2	3	1	2	3	1	2	3	1	2	3
Traffic Light	R	R	R	R	R	R	A	G	G	A	A	A
Participant	EXST3			EXST4			EXST5			EXST6		
Question	1	2	3	1	2	3	1	2	3	1	2	3
Traffic Light	A	A	R	G	G	G	A	G	G	A	G	G
Participant	EXST7			EXST8			EXST9			EXST10		
Question	1	2	3	1	2	3	1	2	3	1	2	3
Traffic Light	A	R	R	A	A	R	G	R	G	R	A	G
Participant	EXST11			EXST12			EXST13			EXST14		
Question	1	2	3	1	2	3	1	2	3	1	2	3
Traffic Light	G	R	A	G	A	G	R	R	A	A	A	G
Participant	EXPG1			EXPG2			EXPG3			EXPG4		
Question	1	2	3	1	2	3	1	2	3	1	2	3
Traffic Light	R	G	G	G	A	A	A	A	A	A	R	A
Participant	EXPG5											
Question	1	2	3									
Traffic Light	R	R	A									

Table 28 shows the traffic light solutions for academic group participants.

Table 28 Traffic light scores for academic group participants

Participant	ECHEMGP1		ECHEMGP2		ECHEMGP3		EPHYSGP1	
Question	1	2	1	2	1	2	1	2
Traffic Light	G	A	A	A	A	A	A	G
Participant	EPHYSGP2		EMIXGP1		EMIXGP2			
Question	1	2	1	2	1	2		
Traffic Light	G	G	A	A	G	G		

Table 29 shows the collected percentage traffic light breakdown for each discipline or group

Table 29 The percentage distribution of red, amber and green solutions for each discipline

Discipline	Red %	Amber %	Green %
Chemistry	31	43	26
Physics	24	41	35
Sports Rehabilitation	67	33	0
Psychology	81	19	0
Interdisciplinary Science	23.5	48	28.5
Pharmacy	76	14	10
Academics	17	46	37
Industrialists	28	33	39
Postgraduates	27	53	20
Academic Groups	0	50	50

For each of the questions each traffic light was assigned a score of Red= 1, Amber= 2 and Green= 3. These scores were totalled together to give each participant a score out of a maximum of 9 and a score out of a maximum of 6 for the group participants.

Each red, amber and green solution was analysed for common themes emerging from the data. Table 30 shows the description of each colour code used for evaluating strategies employed in solving these open-ended problems. All common themes are not present in all of the solutions, but they are common within most of that traffic lighted category:

Table 30 Common themes of red, amber and green solutions with supporting quotes

Colour Code	Emerging characteristics	Quotes
Red	Qualitatively analyses the question, confused by question, unable to develop a strategy, lacks scientific reasoning, struggle to use mathematical concepts, guess at answer, no evaluation of solution, no evaluation of strategy.	*"how many units of alcohol… well you can't really answer that can you?" UHULLPS6* *"If there's a hundred and fifty thousand people… I'd say maybe… I'd say maybe ninety thousand… yeah, no… so if there is sixty thousand. Ok. Yeah. I'm gonna say about fifty thousand… possibly." UHULLCH1*
Amber	Analyses question, identifies required formulas, plans an approach, logical progression of strategy, unsure of scientific concepts, doesn't evaluate their answer, uses prior knowledge and experience, fixate on particular pieces of information, and become distracted by lack of data.	*"I can either do it by mass equation or the density…or the concentration, or the other one. But I need volume." UHULLCH8* *"From festivals I've been to let's say there have been about… maybe 20." UHULLPS8* *"So I do a lot of work with kids and our residential ratio for little girls say Brownies between 7 and 10 is 1:10 approx 1 toilet to 10 people." EXST7*
Green	Qualitatively frames the question, understands what is being asked, models the question, planning, uses scientific concepts, logical strategy, evaluation of answer, evaluation of approach	*"I would have thought that you would have though you would lose an atom every time it at least one revolution is going to remove an atom layer… so I would say it's one circumference so the answer is one revolution of the tyre." EXST4*

4.5 Timeline Analysis

The pencasts were transcribed and the transcripts coded whilst listening to the pencasts using the previously identified codes from section 2.4. The occurrences of each code were listed in chronological order for each problem and catalogued into phases and tabulated. The following sections display the results for the timeline analysis of each discipline. Each table also shows the traffic light code from section 2.8 with the amount of time spent on each question.

Table 31 through Table 39 shows the timeline analysis for the chronological appearance for each approach and when each phase emerged in each cohort.

Table 31 Timeline analysis of approaches in chemistry undergraduate students

Participant		Time	Start													End			
UHULLCH1	Q1	2.59	IIN+	IPF+	IIN+	A&E-	CCP-	EVA+	A&E-	ALG-									
	Q2	10.53	IPF+	IIN+	NDIS -	IIN+	IPF+	A&E+	IIN+	A&E+	IIN+	A&E-	ALG+	NDIS -					
	Q3	12.17	CCP-	IPF+	ALG+	IIN+	ALG+	IIN+	IPF+	ALG+	CCP-	EVA+							
UHULLCH2	Q1	19.00	CCP-	IPF+	CCA-	IIN+	CCP-	IPF+	IIN+	A&E+	IIN+	ALG+							
	Q2	15.09	IIN+	IPF+	A&E+	CCP-	CCA-	ALG+	EVA+	IPF+	A&E+	ALG+	EVA+	CCP-	IPF+	A&E+	ALG+		
	Q3	13.41	IPF+	IIN+	ALG+	CCP-	IPF+	IIN+	ALG+	EVA+	CCA-								
UHULLCH3	Q1	8.08	IPF+	CCP-	IPF+	IIN+	CCP-	IIN+											
	Q2	5.20	IPF+	IIN+	CCP-	A&E+	IPF+	CCP-	ALG+	CCA-									
	Q3	16.15	IPF+	ALG+	IIN+	A&E+	IPF+	CCP-	ALG+	IIN+	IPF+	CCP-	ALG+	CCP-	IIN+	ALG+			
UHULLCH4	Q1	20.00	IPF+	CCP-	IPF+	NDIS -	IIN+	CCP-	IIN+	CCA-	IIN+	NDIS -	IPF+						
	Q2	12.44	IIN+	CCA-	IPF+	IIN+	CCP-	IPF+	A&E+	EVA+	A&E+	ALG+	IPF+	A&E+	ALG+	EVA+			
	Q3	20.00	IIN+	ALG+	IIN+	CCP-	IPF+	IIN+	ALG+	A&E-	ALG+	CCP-	IPF+	IIN+	CCP-	IPF+	ALG+		
UHULLCH5	Q1	20.00	IPF+	IIN+	IPF+	CCA-	ALG+	A&E+	IIN+	A&E+	ALG+	CCP-	NDIS -	IIN+	IPF+	NDIS -	A&E-	EVA+	
	Q2	20.00	IPF+	IIN+	A&E+	IIN+	A&E+	IPF+	ALG+	EVA+	IPF+	CCP-	ALG+	CCP-	A&E-	EVA+	A&E+	ALG+	
	Q3	20.00	IPF+	IIN+	A&E+	CCP-	IPF+	ALG+	EVA+	IPF+	IIN+	ALG+	CCP-	EVA+					
UHULLCH6	Q1	6.32	IPF+	A&E+															
	Q2	5.31	IPF+	A&E+	NDIS -														
	Q3	8.06	IPF+	IIN+	CCP-	NDIS -	ALG+	IIN+											

UHULLCH7	Q1	1.21	IIN+	A&E+	IPF+	ALG+	CCP-												
	Q2	5.15	A&E+	IIN+	A&E+	EVA+	CCP-	ALG+	EVA+	CCP-									
	Q3	7.25	IIN+	IPF+	ALG+	IIN+	EVA+	IIN+	A&E+	IIN+	CCP-	IIN+	ALG+						
UHULLCH8	Q1	9.01	IIN+	IPF+	A&E+	EVA+	ALG+	IIN+	A&E+	EVA+	A&E+	ALG+	EVA+	A&E+	EVA+				
	Q2	11.10	IIN+	A&E+	ALG+	CCP-	ALG+	CCP-											
	Q3	16.17	IIN+	ALG+	IIN+	ALG+	IIN+	ALG+	EVA+	CCP-	ALG+	EVA+	CCP-	ALG+	CCP-	ALG+			
UHULLCH9	Q1	3.23	IIN+	IPF+	A&E+														
	Q2	5.29	IIN+	IPF+	A&E+	IIN+	ALG+												
	Q3	20.00	CCP-	IIN+	ALG+	IIN+	NDIS -	IIN+	IPF+	IIN+	ALG+	CCP-	IPF+	ALG+	CCP-	A&E+	CCP-	CCA-	IIN+
			CCP-	IPF+	CCP-	NDIS -	CCP-	IPF+											
UHULLCH10	Q1	2.07	IIN+	A&E+	IPF+	A&E+	ALG+												
	Q2	2.30	IIN+	IPF+	IIN+	A&E-	ALG+												
	Q3	9.26	IIN+	ALG+	IIN+	CCP-	ALG+	IIN+	A&E+	ALG+	CCP-	IPF+	ALG+	CCP-					
UHULLCH11	Q1	2.12	IIN+	A&E+	ALG+	A&E+													
	Q2	6.15	IPF+	A&E-	EVA+	IIN+	ALG+	NDIS -	ALG+										
	Q3	14.50																	
UHULLCH12	Q1	4.59	IIN+	IPF+	A&E+	ALG+	IIN+	ALG+	CCP-	ALG+	A&E+	CCP-	ALG+	CCA-					
	Q2	7.31	CCP-	IIN+	CCP-	IIN+	CCP-	IIN+	CCP-	CCA-	ALG+	CCP-	CCA-	CCP-	IPF+	ALG+	CCP-	ALG+	CCP-
	Q3	13.51	IIN+	ALG+	IPF+	A&E+	IIN+	CCA-	ALG+	CCP-	ALG+	IPF+	ALG+	IIN+	ALG+	EVA+	IIN+	ALG+	CCA-
			ALG+	CCP-	CCA-	ALG+													
USTRACH1	Q1	2.03	IPF+	A&E+															
	Q2	9.20	IPF+	CCP-	A&E-	CCP-	IIN+	ALG+											

	Q3	20.00	IIN+	IPF+	CCP-	IIN+	CCA-	CCP-	EVA+	A&E-	CCP-	ALG+	IIN+	CCP-	IIN+	ALG+	EVA+	CCA-	
USTRACH2	Q1	5.59	IIN+	IPF+	A&E+	ALG+													
	Q2	8.11	IIN+	CCP-	IIN+	A&E+	IPF+	CCP-	IIN+	CCA-									
	Q3	16.59	IIN+	ALG+	IPF+	ALG+	IIN+	ALG+	IIN+	IPF+	IIN+	ALG+	CCP-	EVA+	IIN+	ALG+			
USTRACH3	Q1	10.54	IIN+	CCP-	IIN+	CCP-	IPF+	IIN+	ALG+	A&E+	CCA-	IPF+	CCP-	EVA+	ALG+				
	Q2	11.43	CCP-	CCA-	IIN+	IPF+	NDIS -	IIN+	IPF+	IIN+	IPF+	DAS+	NDIS -	IIN+	ALG+				
	Q3	20.00	IIN+	CCA-	IPF+	ALG+	CCP-	IPF+	A&E+	IIN+	CCP-	IIN+	NDIS -	CCP-	IIN+	IPF+	CCP-	IIN+	EVA+
			ALG+	CCP-	ALG+	CCA-	EVA+												
USTRACH4	Q1	5.33	IIN+	IPF+	IIN+	A&E+	NDIS -												
	Q2	6.54	IPF+	IIN+	A&E+	NDIS -	CCA-	IIN+	CCA-	IIN+									
	Q3	19.16	IIN+	IPF+	IIN+	IPF+	CCA-	ALG+	CCP-	CCA-	ALG+	EVA+							
USTRACH5	Q1	9.55	IIN+	IPF+	A&E+	CCP-	CCA-	ALG+	CCP-	EVA+									
	Q2	10.19	IIN+	IPF+	IIN+	CCP-	IIN+	IPF+	A&E+	ALG+	EVA+								
	Q3	9.16	IIN+	IPF+	IIN+	ALG+	IIN+	ALG+	CCP-	ALG+	EVA+	ALG+							

Table 32 Timeline analysis of approaches in physics undergraduate students

Participant		Time	Start													End			
UHULLPH1	Q1	6.38	IIN+	A&E+	IIN+	CCA-	A&E+	IPF+	ALG+	IIN+	IPF+	ALG+							
	Q2	7.41	IIN+	CCP-	IPF+	A&E+	ALG+	IIN+	A&E-	CCP-	ALG+								
	Q3	17.18	CCP-	IIN+	IPF+	IIN+	ALG+	CCA-	IIN+	IPF+	CCA-	ALG+	CCA-	CCP-	ALG+	IIN+	A&E-	IIN+	ALG+
UHULLPH2	Q1	3.44	IIN+	A&E+	IIN+	A&E+	DAS+	ALG+	CCP-										
	Q2	4.22	CCP-	IIN+	CCA-	CCP-	A&E+	IPF+	ALG+	IIN+	A&E+	NDIS-	ALG+	CCP-	EVA+	ALG+	NDIS-		
	Q3	6.29	IIN+	ALG+	CCP-	ALG+	EVA+	CCP-	IPF+	CCP-	ALG+	CCP-	ALG+	EVA+					
UHULLPH3	Q1	5.14	IIN+	DAS+	A&E+	IIN+	A&E+	CCP-	EVA+										
	Q2	6.45	IIN+	CCP-	NDIS-	IIN+	CCP-	A&E+	CCP-	ALG+	CCP-	EVA+							
	Q3	6.13	IIN+	IPF+	IIN+	ALG+	IIN+	EVA+											
UHULLPH4	Q1	2.25	IIN+	IPF+															
	Q2	4.01	CCP-	IIN+	IPF+														
	Q3	8.18	IIN+	A&E+	ALG+	IIN+	ALG+	CCP-	IIN+	ALG+									
UHULLPH5	Q1	9.35	IPF+	IIN+	A&E+	ALG+	A&E-												
	Q2	15.20	IIN+	A&E+	IIN+	A&E+	IPF+	ALG+	IPF+	IPF+	IIN+	A&E+	ALG+	CCP-					
	Q3	17.16	A&E+	ALG+	IPF+	ALG+	CCP-	IIN+	ALG+	IIN+	ALG+	CCP-	ALG+						
UHULLPH6	Q1	12.25	IIN+	IPF+	A&E+	IIN+	ALG+	IPF+	CCP-	NDIS-	A&E+	ALG+	EVA+	CCP-	IPF+	A&E-	ALG+	EVA-	ALG+
			EVA+																
	Q2	14.35	IPF+	CCP-	IPF+	A&E-	ALG+	EVA+	A&E+	ALG+	IIN+	ALG+	CCP-	IIN+	A&E+	CCP-	ALG+	EVA+	CCP-
			NDIS-	IPF+															
	Q3	19.04	IPF+	IIN+	A&E+	CCP-	IPF+	CCP-	IPF+	ALG+	CCA-	ALG+	CCP-	ALG+	IPF+	ALG+	IIN+	IPF+	CCA-
			ALG+	IIN+	IPF+	IIN+	CCP-	ALG+	EVA+	ALG+									

UHULLPH7	Q1	3.08	IPF+	IIN+	ALG+	IIN+	A&E+												
	Q2	9.00	IIN+	A&E+	IIN+	ALG+	A&E+	IPF+	A&E+	ALG+	CCP-	EVA+	IPF+	ALG+	CCP-	IPF+			
	Q3	2.48	IIN+	IPF+	IIN+	A&E+	ALG+	A&E+											
UHULLPH8	Q1	13.43	A&E+	IPF+	CCP-	A&E+	IPF+	ALG+	EVA+	ALG+	IPF+	ALG+	A&E+	IIN+	ALG+	EVA+	ALG+		
	Q2	13.32	A&E+	IPF+	ALG+	IIN+	CCA-	IIN+	CCP-	IIN+	ALG+	EVA+	IIN+	CCP-	NDIS-	ALG+	A&E+	CCP-	IPF+
			A&E+	ALG+															
	Q3	20.00	IPF+	A&E+	ALG+	IPF+	IIN+	NDIS-	CCP-	A&E+	IPF+	EVA+	IPF+	A&E+	ALG+	EVA+	ALG+	IIN+	A&E+
			IPF+																
UHULLPH9	Q1	7.31	IPF+	IIN+	A&E+	ALG+	A&E+	ALG+	EVA+	ALG+	EVA+	CCP-	NDIS-						
	Q2	20.00	IPF+	IIN+	IPF+	NDIS-	A&E+	IIN+	ALG+	IIN+	A&E+	ALG+	CCP-	NDIS-	ALG+	EVA+	ALG+	IIN+	CCP-
			IIN+	ALG+															
	Q3	20.00	IIN+	IPF+	A&E+	IPF+	A&E+	A&E-	A&E+	IPF+	ALG+	IIN+	ALG+	CCP-	IIN+	ALG+	IIN+	A&E-	CCP-
			ALG+																
UHULLPH10	Q1	7.12	ALG	IPF+	IIN+	CCP-	ALG+	IIN+	CCP-	IPF+	A&E+	ALG+							
	Q2	19.55	CCP-	IPF+	IIN+	NDIS-	CCP-	IIN+	ALG+	A&E+	NDIS-	IPF+	CCP-	CCA-	NDIS-	EVA+	IIN+	ALG+	EVA+
	Q3	20.00	CCP-	IIN+	IPF+	IIN+	NDIS-	IIN+	A&E+	IIN+	CCP-	CCA-	A&E+	IIN+	ALG+	EVA+	CCP-	IPF+	IIN+
			IPF+	CCP-	IIN+	ALG+	CCP-												
UEDINPH1	Q1	12.41	IIN+	IPF+	IIN+	CCP-	IIN+	NDIS-	IIN+	CCP-	A&E+	IPF+	CCP-	DAS+	ALG+	CCP-	ALG+		
	Q2	6.44	CCP-	IPF+	DAS+	IIN+	A&E+	CCP-	ALG+	DAS+	CCP-	A&E+	ALG+						
	Q3	13.57	IPF+	A&E+	IIN+	NDIS-	IIN+	A&E+	ALG+	A&E+	A&E+	CCA-	DAS+	ALG+	EVA+	ALG+			
UEDINPH2	Q1	2.04	IIN+	IPF+	A&E+	IIN+	CCP-												
	Q2	5.18	CCA-	IPF+	CCA-	A&E+	IIN+	DAS+	IIN+	A&E+	IPF+	ALG+	CCP-	EVA+					
	Q3	5.22	IPF+	CCP-	IIN+	ALG+													
UEDINPH3	Q1	4.44	IIN+	CCP-	CCA-	IIN+	CCA-	IPF+	CCA-	IIN+	CCA-	A&E+	CCP-	A&E+	CCP-	EVA+	ALG+	A&E+	ALG+

			CCP-																
	Q2	5.16	CCA-	CCP-	IPF+	IIN+	IPF+	IIN+	ALG+	IPF+	CCA-	CCP-	IIN+	DAS+	IIN+	A&E+	EVA+	ALG+	A&E+
			EVA+																
	Q3	9.41	CCP-	IIN+	CCP-	DAS+	IPF+	ALG+	IIN+	ALG+	IIN+	A&E+	ALG+						
UEDINPH4	Q1	2.08	IPF+	IIN+	IPF+	DAS+	A&E+												
	Q2	6.26	CCP-	IPF+	A&E+	IIN+	CCP-	IPF+	CCP-	IPF+	IIN+	ALG+	CCP-	IIN+	DAS+	CCP-	CCA-	ALG+	EVA+
	Q3	7.17	IIN+	IPF+	CCP-	IIN+	ALG+	IIN+	CCP-	IIN+	DAS+	EVA+	ALG+	IPF+	EVA+	ALG+	EVA+	CCP-	
UEDINPH5	Q1	8.44	IIN+	CCP-	IPF+	IIN+	IPF+	A&E+	DAS+	ALG+	A&E+	CCP-	EVA+	NDIS +	CCP-				
	Q2	13.25	IPF+	CCP-	IIN+	IPF+	IIN+	CCP-	IIN+	CCP-	IPF+	CCP-	IIN+	CCP-	IIN+	CCP-	IPF+	IIN+	IPF+
			CCP-	IIN+	CCP-	DAS+	CCP-	EVA+	A&E+	ALG+									
	Q3	7.05	CCP-	IIN+	CCP-	IPF+	DAS+	IIN+	DAS+	ALG+									
UEDINPH6	Q1	3.36	IIN+	A&E+	IPF+	CCA-	DAS+	IPF+	EVA+	CCA-	A&E+								
	Q2	3.31	A&E+	IIN+	CCP-	EVA+	ALG+	EVA+											
	Q3	8.16	IIN+	ALG+	IIN+	A&E+	A&E+	IIN+	IPF+	CCP-	CCA-	ALG+							
UEDINPH7	Q1	3.20	IIN+	A&E+	CCP-	A&E+	ALG+												
	Q2	13.28	IIN+	DAS+	CCA-	NDIS-	IIN+	A&E+	CCP-	IIN+	IPF+	IIN+	CCA-	IIN+	A&E+	IPF+	ALG+	CCP-	IIN+
			A&E+	ALG+	IIN+	A&E+	CCA-	CCP-	IIN+	IPF+	CCP-	IIN+	A&E+	ALG+	CCP-	EVA+			
	Q3	4.19	IIN+	DAS+	IIN+	ALG+													

Table 33 Timeline analysis of approaches in sports rehabilitation undergraduate students

Participants		Time	Start														End		
UHULLSR1	Q1	1.38	A&E-	EVA-															
	Q2	1.39	CCA-	A&E-	CCA-														
	Q3	2.10	CCA-	IPF+	CCP-	A&E+													
UHULLSR2	Q1	1.43	CC+																
	Q2	1.44	IIN+	A&E+	ALG+														
	Q3	6.07	IIN+	A&E-	ALG+	IIN+	CCA-	IIN+	A&E-										
UHULLSR3	Q1	1.53	IIN+	IPF+															
	Q2	1.26	CCP-	IPF+	A&E-														
	Q3	3.17	IPF+	CCA-	A&E+														
UHULLSR4	Q1	5.25	IIN+	IPF+	CCP-	IIN+	CCP-	A&E-											
	Q2	5.37	IPF+	CCA-	CCP-	IIN+	CCP-	IIN+	A&E+	A&E-	CCP-								
	Q3	10.49	IPF+	IIN+	CCP-	IIN+	IPF+	A&E+	IPF+	A&E+	IIN+	CCA-	CCP-	CCA-	CCP-	IIN+	CCA-	CCP-	CCA-
UHULLSR5	Q1	2.29	IIN+	CCP-	A&E+	CCP-													
	Q2	3.12	IIN+	IPF+	IIN+	CCA-	CCP-												
	Q3	7.29	IIN+	IPF+	DAS+	IPF+	A&E+	ALG+	CCA-	CCP-									
UHULLSR6	Q1	1.55	CCP-	IPF+	IIN+	A&E+	ALG+	EVA+	A&E+										
	Q2	2.58	IPF+	CCP-	IPF+	IIN+	A&E+												
	Q3	6.04	A&E+	IPF+	IIN+	A&E-	ALG+	A&E+	CCP-	ALG+									

Table 34 Timeline analysis of approaches in psychology undergraduate students

Participant		Time	Start														End		
UHULLPS1	Q1	2.14	CCP-	A&E-	ALG+	CCP-	IPF+												
	Q2	2.50	CCP-	A&E+	ALG+	A&E+	IIN+	CCP-	LSA-	A&E+									
	Q3	3.47	CCA-	CCP-	A&E-	LSA-	CCA-	CCP-											
UHULLPS2	Q1	1.31	CC+	A&E-															
	Q2	2.45	A&E+	EVA+	A&E+														
	Q3	1.34	CCP-	A&E-															
UHULLPS3	Q1	3.18	IIN+	IPF+	IIN+	A&E+	CCP-	CCA-	CCP-	CCA-	IIN+	A&E+	CCA-						
	Q2	3.44	IPF+	NDIS-	IPF+	A&E+	NDIS-	A&E+											
	Q3	7.24	IIN+	A&E+	IPF+	A&E+	NDIS-	CCA-	EVA+	CCP-	A&E+								
UHULLPS4	Q1	1.45	IPF+	A&E-	A&E+	NDIS+													
	Q2	1.06	A&E+	IPF+	A&E+														
	Q3	1.53	A&E-	EVA-															
UHULLPS5	Q1	9.22	IPF+	CCP-	IIN+	IPF+	CCP-	NDIS-	A&E+	CCP-									
	Q2	12.43	IPF+	CCP-	IPF+	NDIS-	CCP-												
	Q3	10.27	IPF+	CCP-	NDIS-	CCP-													
UHULLPS6	Q1	2.28	IPF+	NDIS-	CCP-	IIN+	CCA-	NDIS-	CCP-	A&E-	CCP-	A&E-	CCP-						
	Q2	3.56	IIN+	CCA-	IIN+	CCP-	IIN+	NDIS-	CCP-	NDIS-									
	Q3	2.11	CCP-	IPF+	CCP-	A&E+	NDIS-	CCP-											
UHULLPS7	Q1	1.55	IIN+	A&E-	CCP-														
	Q2	2.59	IIN+	CCA-	A&E+	CCP-	A&E+												
	Q3	2.26	CCP-	A&E-	DAS-														

UHULLPS8	Q1	3.22	IIN+	IPF+	CCA-	CCP-	A&E+												
	Q2	3.40	IPF+	NDIS-	A&E+	DAS+	IPF+	A&E+	NDIS-	A&E-									
	Q3	12.45	CCP-	IPF+	CCP-	IIN+	A&E-	A&E+	LSA+	IPF+	NDIS-								
UHULLPS9	Q1	0.42	A&E-																
	Q2	1.04	CCP-	A&E-	DAS+														
	Q3	1.06	IPF+	A&E+															

Table 35 Timeline analysis of approaches in inter-disciplinary science undergraduate students

Participants		Time	Start														End		
ULEIISCI1	Q1	8.12	IIN+	IPF+	CCA-	IPF+	A&E+	ALG+	CCP-	A&E+	NDIS-								
	Q2	2.47	IIN+	IPF+	A&E+	IPF+	ALG+												
	Q3	8.22	IIN+	IPF+	IIN+	IPF+	ALG+	IIN+	ALG+										
ULEIISCI2	Q1	2.04	IIN+	IPF+	A&E+	ALG+													
	Q2	4.41	IIN+	IPF+	A&E+	IIN+	CCP-	A&E+	ALG+										
	Q3	5.19	IIN+	A&E+	IPF+	ALG+													
ULEIISCI3	Q1	6.48	IIN+	IPF+	A&E+	IPF+	IIN+	A&E+	IPF+										
	Q2	6.27	IPF+	IIN+	NDIS-	IPF+	IIN+	IPF+											
	Q3	10.46	IIN+	IPF+	IIN+	IPF+	NDIS-	IIN+	A&E+	ALG+	IIN+								
ULEIISCI4	Q1	20.00	IIN+	IPF+	ALG+	IIN+	IPF+	ALG+	EVA+	CCP-	ALG+	EVA+	ALG+	CCP-	A&E+	IPF+	EVA+	CCP-	NDIS-
			A&E+	IIN+	IPF+	ALG+													
	Q2	20.00	IPF+	IIN+	IPF+	A&E+	IPF+	ALG+	A&E-	CCP-	A&E+	ALG+	IPF+	CCA-	IIN+	EVA+	ALG+	EVA-	ALG+
			NDIS-																
	Q3	20.00	IIN+	IPF+	A&E+	ALG+	IPF+	IIN+	IPF+	CCP-	A&E+	IPF+	CCP-	A&E+	CCP-	ALG+	NDIS-	IPF+	
ULEIISCI5	Q1	20.00	IIN+	IPF+	A&E+	A&E-	ALG+	IIN+	IPF+	A&E+	CCA-	CCP-	EVA+	A&E+	ALG+	EVA+	IPF+	IIN+	A&E-
			IPF+	CCP-	IPF+	ALG+	EVA-	IPF+	EVA+	CCP-	NDIS-								
	Q2	20.00	IIN+	CCP-	IPF+	IIN+	NDIS-	CCP-	IIN+	IPF+	CCA-	IPF+	IIN+	CCP-	IIN+	A&E+	IIN+	EVA+	ALG+
			CCP-	EVA+															
	Q3	20.00	IIN+	IPF+	A&E+	ALG+	IIN+	ALG+	CCA-	IIN+	ALG+	CCP-	EVA+	CCP-	IPF+	IIN+	A&E-	A&E+	ALG+
ULEIISCI6	Q1	6.34	CCP-	A&E-	A&E+	IPF+	ALG+	EVA+	A&E+	IPF+									
	Q2	11.53	IPF+	A&E+	IPF+	IIN+	IPF+	EVA+	IIN+	A&E+	IIN+	EVA+	IIN+	ALG+	CCP-	IPF+			
	Q3	11.17	IIN+	IPF+	ALG+	CCP-	ALG+	CCA-	EVA+	IIN+	ALG+	EVA+							

ULEIISCI7	Q1	2.21	IIN+	A&E+	IPF+	ALG+	CCA-												
	Q2	3.01	CCA-	IPF+	IIN+	NDIS-	CCP-	IPF+	IIN+										
	Q3	8.09	IIN+	A&E+	IIN+	IPF+	CCA-	ALG+											

Table 36 Timeline analysis of approaches in pharmacy undergraduate students

Participant		Time	End													Start			
UMONPHAR1	Q1	14.29	IPF+	IIN+	CCP-	IPF+	IIN+	IPF+	IIN+	A&E+	IPF+	ALG+	CCP-	ALG+					
	Q2	8.21	CCP-	IPF+	IIN+	IPF+	IIN+	A&E+	ALG+	IIN+	ALG+								
	Q3	7.36	A&E+	IIN+	IPF+	IIN+	A&E+	ALG+	EVA+	IPF+	NDIS -	IIN+	IPF+						
UMONPHAR2	Q1	1.21	IPF+	IIN+	A&E-														
	Q2	5.45	IIN+	NDIS -	CCP-	IIN+	IPF+	CCP-											
	Q3	7.33	IIN+	NDIS -	CCP-	IIN+	CCP-	IPF+	IIN+	NDIS -	IIN+	IPF+							
UMONPHAR3	Q1	11.10	IPF+	NDIS -	IIN+	IPF+	CCP-	NDIS -	A&E-	ALG+	EVA+	CCP-	CCA-	ALG+	EVA+				
	Q2	3.43	IIN+	IPF+	IIN+	NDIS -	IPF+	A&E-	NDIS -	CCA-									
	Q3	4.25	IPF+	IIN+	NDIS -	IPF+	CCP-	CCA-											
UMONPHAR4	Q1	2.13	IPF+	A&E-	NDIS -														
	Q2	3.06	A&E-	IPF+	A&E-	NDIS -	IPF+												
	Q3	2.14	A&E-	IPF+	NDIS -														
UMONPHAR5	Q1	9.30	IPF+	IIN+	ALG+	EVA+	CCP-	NDIS -	IPF+	A&E-	EVA-	CCP-	IPF+						
	Q2	11.59	IPF+	CCP-	A&E-	EVA-	NDIS -	IPF+	NDIS -	A&E-	IIN+								
	Q3	11.24	IPF+	IIN+	A&E-	IPF+	NDIS -	CCP-	EVA-	IPF+	NDIS -	CCP-	EVA+						

UMONPHAR6	Q1	6.14	IIN+	IPF+	CCP-	A&E-	ALG+												
	Q2	16.28	IIN+	IPF+	IIN+	CCP-	IPF+	NDIS -	A&E-	CCP-	CCA-	IPF+	NDIS -	ALG+	NDIS -	EVA+	NDIS -		
	Q3	13.25	IPF+	IIN+	ALG+	NDIS -	CCP-	IPF+	ALG+	NDIS -									
UMONPHAR7	Q1	1.03	IIN+	A&E-	NDIS -														
	Q2	2.33	IIN+	CCP-	A&E+	ALG+	IPF+												
	Q3	4.33	IIN+	IPF+	CCP-	IPF+	A&E+	CCP-	NDIS -	IPF+	ALG+								
UMONPHAR8	Q1	0.24	A&E-																
	Q2	4.02	IPF+	IIN+	A&E+	A&E-	ALG+	CCP-	IPF+	A&E-									
	Q3	2.41	A&E+	ALG+	IPF+	CCP-	ALG+												
UMONPHAR9	Q1	5.20	IPF+	CCP-	IPF+	NDIS -	IPF+	A&E+	CCP-	ALG+	A&E+								
	Q2	7.48	CCP-	IPF+	CCP-	NDIS -	IPF+	CCP-	IPF+	EVA+	NDIS -	IIN+	A&E-						
	Q3	7.27	CCP-	IIN+	IPF+	IIN+	NDIS -	IIN+	A&E-	ALG+	CCA-	NDIS -							
UMONPHAR10	Q1	1.57	IPF+	IIN+	IPF+	A&E-	A&E+												
	Q2	6.19	IPF+	IIN+	IPF+	A&E-	A&E+	IIN+	IPF+	IIN+	CCP-	ALG+	CCA-	CCP-					
	Q3	11.15	IPF+	IIN+	IPF+	CCP-	CCA-	ALG+	CCP-	EVA+	IPF+	A&E-	ALG+	A&E-	ALG+	EVA+	NDIS -		
UMONPHAR11	Q1	8.26	IPF+	CCP-	IPF+	NDIS -	A&E-	NDIS -											
	Q2	5.26	IPF+	A&E-	IIN+	ALG+	CCP-	NDIS -											
	Q3	5.32	IPF+	EVA+	A&E+	IIN+	ALG+	EVA+											

UMONPHAR12	Q1	15.10	IPF+	A&E+	IPF+	A&E-	IIN+	EVA+	A&E+	ALG+	IPF+	EVA+							
	Q2	16.09	IIN+	CCA-	ALG+	EVA-	IIN+	IPF+	A&E+	NDIS-	A&E+	IPF+	A&E+	ALG+	IIN+	EVA+	CCP-	IPF+	A&E+
			EVA+																
	Q3	17.17	IIN+	CCP-	IPF+	IIN+	CCP-	IPF+	A&E+	A&E-	IPF+	EVA+	A&E+	ALG+	EVA+	ALG+	EVA+		
UMONPHAR13	Q1	10.15	IPF+	NDIS-	IIN+	IPF+	IIN+	CCP-											
	Q2	15.28	IPF+	IIN+	IPF+	CCP-	IIN+	NDIS-	IPF+	IIN+	CCP-	IIN+	CCP-	IIN+	IPF+	IIN+	NDIS-	IIN+	NDIS-
	Q3	18.09	IIN+	IPF+	IIN+	IPF+	IIN+	NDIS-	IIN+	CCP-	IIN+	IPF+	NDIS-	ALG+	IPF+	IIN+	CCP-	IPF+	
UMONPHAR14	Q1	3.49	IPF+	A&E-	CCP-	CCA-	NDIS-												
	Q2	5.19	IPF+	NDIS-	IPF+	A&E-													
	Q3	6.30	IPF+	NDIS-	A&E-														

Table 37 Timeline analysis of approaches in academic participants

Participants		Time	Start														End		
EXST1	Q1	2.57	IPF+	IIN+	A&E+	ALG+	EVA+	IPF+	A&E+	EVA+	ALG+								
	Q2	9.06	IPF+	IIN+	A&E+	EVA+	ALG+	LSA+	DAS+	ALG+	EVA+	ALG+	EVA+	CCP-					
	Q3	6.22	IIN+	IPF+	IIN+	IPF+	CCP-	IIN+	ALG+	EVA+	NDIS+	EVA+	ALG+	CCP-	EVA+				
EXST2	Q1	3.09	IPF+	CCP-															
	Q2	7.08	IPF+	CCP-															
	Q3	18.11	CCP-	IIN+	CCP-	IPF+	IIN+	CCP-	IPF+	IIN+	CCA-	CCP-	ALG+	CCP-	EVA+	IPF+	ALG+	CCP-	
EXST3	Q1	2.47	IPF+	A&E+	ALG+	IPF+													
	Q2	19.56	IPF+	IIN+	CCA-	A&E+	IIN+	EVA+	NDIS-	CCP-	IIN+	DAS+	ALG+						
	Q3	10.32	IIN+	DAS+	IIN+	CCP-	ALG+	CCP-	IIN+	ALG+									
EXST4	Q1	5.14	IIN+	A&E+	IPF+	IIN+	IPF+	A&E+	IIN+	A&E+									
	Q2	2.54	IIN+	A&E+	IPF+	A&E+													
	Q3	10.10	IPF+	A&E+	IIN+	DAS+	IIN+	IPF+	ALG+	EVA+									
EXST5	Q1	4.28	IIN+	IPF+	A&E+	ALG+	CCP-	IPF+											
	Q2	2.01	IPF+	IIN+	A&E+	IIN+	ALG+	A&E+											
	Q3	20.00	IIN+	CCP-	IIN+	CCA-	A&E+	IIN+	DAS+	CCP-	ALG+	CCA-	ALG+	CCP-	EVA+	ALG+	IPF+	CCP-	EVA+
			CCA-	NDIS+	CCA-	CCP-	CCA-	IIN+	ALG+										
EXST6	Q1	7.37	IIN+	IPF+	A&E+	IPF+	ALG+	EVA+	ALG+	EVA+									
	Q2	1.44	NDIS-	IIN+	A&E+	ALG+													
	Q3	11.28	IIN+	IPF+	DAS+	A&E+	IIN+	ALG+	IIN+	NDIS-	IIN+	A&E-	ALG+	A&E+	EVA+				
EXST7	Q1	13.37	IIN+	IPF+	A&E+	CCP-	A&E+	EVA+	IIN+	CCA-	IIN+	CCP-	A&E+	CCA-	IIN+	A&E+	CCP-	EVA+	CCP-
			CCP-	EVA+	ALG+														

	Q2	20.00	IIN+	CCP-	A&E+	IIN+	EVA+	CCA-	IIN+	A&E+	DAS+	A&E+	CCA-	EVA+	CCP-	IIN+	NDIS-	CCP-	EVA+
			CCP-	EVA+	ALG+	EVA+	CCP-	DAS+	CCA-										
	Q3	15.10	CCP-	IPF+	IIN+	DAS+	IPF+	CCP-	IIN+	A&E+	ALG+	CCA-	ALG+	IPF+	DAS+	A&E+	NDIS-	CCA-	NDIS-
			EVA+	NDIS-	CCP-	ALG+	IIN+	IPF+	CCP-										
EXST8	Q1	6.44	IPF+	IIN+	A&E+	ALG+													
	Q2	3.43	IIN+	NDIS-	DAS+	A&E-	NDIS-	CCP-											
	Q3	7.41	IPF+	DAS+	IIN+	EVA+	DAS+	NDIS-	CC+	IIN+									

Table 38 Timeline analysis of approaches in industrialist participants

Participants		Time	Start													End		
EXST9	Q1	10.43	IPF+	IIN+	CCP-	IIN+	IPF+	IIN+	A&E+	CCA-	ALG+	EVA+	CCP-	CCA-	IPF+	EVA+			
	Q2	6.15	IIN+	IPF+	IIN+	CCA-	IIN+	CCP-	IIN+	IPF+	EVA+								
	Q3	10.30	IIN+	ALG+	IPF+	ALG+	CCA-	ALG+	IIN+	ALG+	EVA+								
EXST10	Q1	2.22	IIN+	A&E+	IIN+	IPF+													
	Q2	1.04	IPF+	IIN+	IPF+	A&E+													
	Q3	13.35	IPF+	IIN+	A&E+	IIN+	ALG+	EVA+	CCP-	CCA-	ALG+	CCP-	ALG+	EVA+	CCP-	ALG+	EVA+		
EXST11	Q1	8.15	CCP-	IPF+	IIN+	IPF+	EVA+	A&E+	ALG+	EVA+	CCP-	CCA-	ALG+	IIN+	ALG+				
	Q2	12.40	CCP-	IPF+	CCP-	IIN+	CCP-	IPF+	CCP-	ALG+									
	Q3	8.59	IPF+	IIN+	A&E+	IPF+	IIN+	CCP-	ALG+										
EXST12	Q1	12.28	IPF+	IIN+	A&E+	IPF+	CCP-	A&E+	ALG+	EVA+	CCP-	IPF+	ALG+	A&E+	CCP-	EVA+	ALG+	EVA+	
	Q2	16.36	IPF+	IIN+	IPF+	A&E+	IIN+	IPF+	IIN+	CCP-	ALG+	CCA-	ALG+	EVA+	CCP-	CCA-	ALG+	EVA+	CCP-
	Q3	14.11	IIN+	IPF+	ALG+	CCA-	CCP-	ALG+	EVA+	IPF+	ALG+	CCA-	ALG+	EVA+	CCA-	ALG+	CCP-	ALG+	
EXST13	Q1	8.40	IPF+	IIN+	IPF+	IIN+	CCA-	IPF+	IIN+	CCA-									
	Q2	9.52	IPF+	IIN+	IPF+														
	Q3	20.00	IIN+	IPF+	IIN+	EVA+	CCA-	IPF+	ALG+	CCP-	ALG+	EVA+	ALG+	CCA-	ALG+	IPF+	IIN+	IPF+	IIN+
			IPF+																
EXST14	Q1	12.18	IPF+	IIN+	IPF+	A&E+	CCP-	NDIS-	A&E+	ALG+	IPF+	ALG+	EVA+	IPF+	CCA-				
	Q2	16.00	CCP-	IPF+	CCP-	IIN+	ALG+	A&E+	ALG+	IPF+	CCA-	IPF+	ALG+	NDIS-					
	Q3	11.01	IPF+	IIN+	IPF+	IIN+	CCA-	ALG+	EVA+	ALG+	CCA-	ALG+	CCA-	EVA+	IIN+	ALG+			

Table 39 Timeline analysis of approaches in chemistry postgraduate students

Participants		Time	Start													End		
EXPG1	Q1	1.59	IIN+	A&E+	IIN+													
	Q2	2.44	CCP-	IPF+	IIN+	CCP-	A&E+	ALG+										
	Q3	11.44	IIN+	IPF+	IIN+	ALG+	CCA-	IIN+	ALG+	EVA+	CCP-	ALG+	IIN+	ALG+					
EXPG2	Q1	4.54	IIN+	A&E+	IIN+	A&E+	IIN+	ALG+	CCP-										
	Q2	14.01	IIN+	A&E+	IPF+	ALG+	A&E+	ALG+	IPF+	CCP-	A&E+	IPF+	A&E+	ALG+	A&E+	ALG+	A&E+	ALG+	
	Q3	20.00	A&E+	IPF+	CCP-	A&E+	ALG+	CCP-	A&E-	ALG+	A&E-	ALG+	A&E-	IIN+	CCP-	EVA+	CCA-	CCP-	A&E+
			ALG+	CCP-	ALG+	CCP-	ALG+	CCP-	ALG+	CCA-	ALG+	EVA+	CCA-	CCP-	ALG+	NDIS-	ALG+		
EXPG3	Q1	5.18	IIN+	A&E+	CCP-	IPF+	A&E-	EVA+	A&E-	NDIS-									
	Q2	10.03	IIN+	IPF+	IIN+	IPF+	IIN+	EVA+	A&E+	ALG+	IPF+	CCP-	ALG+	EVA+	CCA-				
	Q3	9.56	IIN+	A&E+	CCP-	CCA-	IIN+	CCA-	ALG+	IIN+	A&E-	IIN+	ALG+	IPF+	ALG+				
EXPG4	Q1	5.20	IPF+	A&E+	IPF+	A&E+	ALG+	A&E+	EVA+	A&E+	ALG+	A&E+	IPF+						
	Q2	7.32	IIN+	IPF+	A&E+	NDIS-	IPF+	CCP-	A&E+	IPF+	CCP-								
	Q3	11.43	IPF+	A&E+	CCP-	CCA-	A&E+	IIN+	IPF+	ALG+	IPF+	IIN+	ALG+	IPF+	EVA+				
EXPG5	Q1	5.46	IPF+	A&E+	ALG+	CCP-	CCA-	EVA+	A&E+	ALG+	CCP-	IPF+	EVA+	ALG+	NDIS-				
	Q2	5.40	CCP-	IPF+	IIN+	A&E+	ALG+	CCP-	A&E+	ALG+	NDIS-								
	Q3	16.55	IPF+	A&E+	IPF+	ALG+	CCA-	ALG+	CCP-	ALG+	EVA+	A&E+	ALG+	EVA+	ALG+	EVA+	ALG+	CCP-	ALG+
			CCA-	ALG+	CCP-	ALG+	A&E+	ALG+											

5 Quantitative Result

This section presents the quantitative data that was collected using the Figural Intersection Test (FIT) and the Group Embedded Figures Test (GEFT), how these scores relate to each other and the qualitative approaches outlined in section 4.1.

5.1 FIT Results

This section presents the results from the data collected using the FIT 8303 PS test as identified in section 3.1.1. These results have been represented as raw score data as a histogram as seen in Figure 40, as calculated through the FIT-1 scoring method.

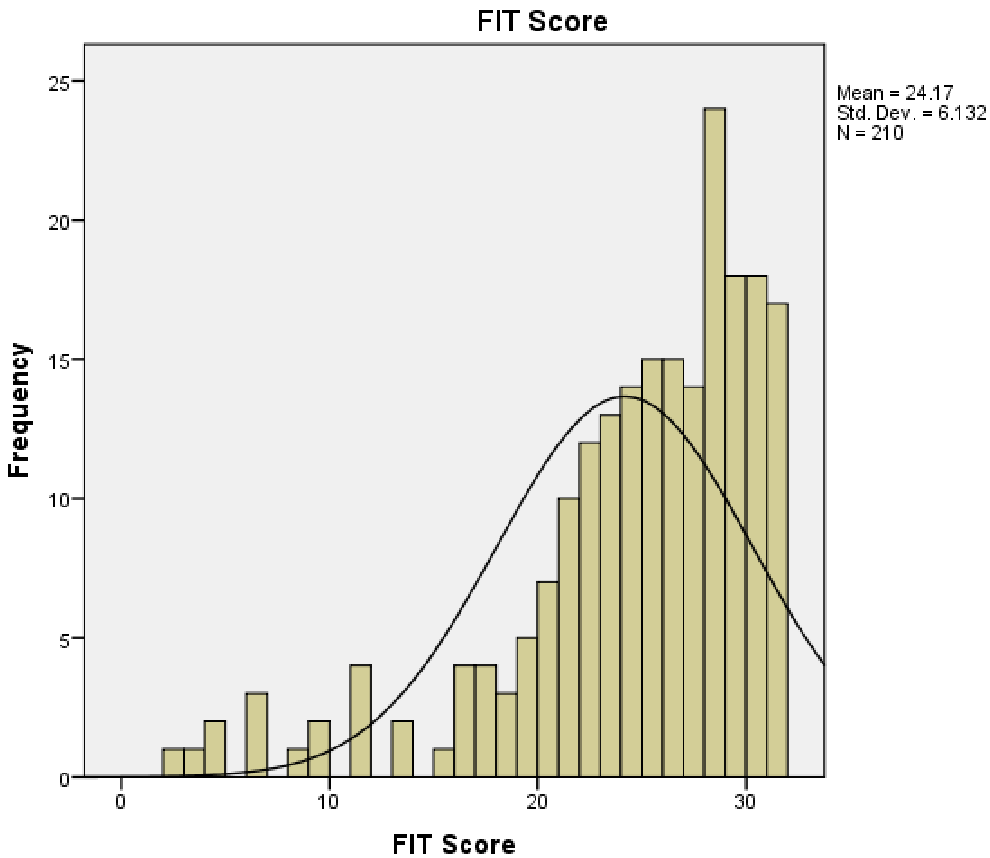

Figure 39 Graph showing the raw scores for the FIT from all participants.

The data shows that participants showed a tendency towards upper end values on the FIT test (*n*= 210, SD= 6.132, M= 24.17, skewness = -1.508, Kurtosis = 2.343). It would be expected that the population at university would score high because they have demonstrated inherent intelligence by achieving A-levels and participating in a university degree program.

The FIT scores for the participants who were involved in the qualitative study in section 4.1 were assessed for correlations against the percentage values for the occurrence of each qualitative code. The data was analysed using Pearson's Correlation where the data is assumed to be normally distributed and linear in nature. The data reported here are where there were some significant correlations on the Pearson's correlation test observed (Table 41).

Table 40 Pearson's correlation for GEFT scores against % distribution of approaches.

	FIT Score		
	Spearman's Rho	Sig (2-tailed)	*N*=
FIT Score	1	-	210
IIN+%	0.231	0.087	56
A&E+%	0.139	0.307	56
ALG+%	0.082	0.549	56
EVA+%	0.151	0.267	56
IPF+%	-0.061	0.655	60
DAS+%	0.042	0.750	60
NDIS+%	-0.077	0.560	60
LSA+%	0.020	0.879	56
IIN-%	-0.340*	0.010	56
A&E-%	-0.119	0.380	56
ALG-%	-0.188	0.166	56
EVA-%	-0.098	0.547	60
IPF-%	-0.007	0.958	56
DAS-%	-0.229	0.090	56
NDIS-%	-0.035	0.798	56
LSA-%	-0.112	0.411	56
CC+%	-0.094	0.490	56
CCP-%	0.008	0.954	56
CCA-%	0.000	0.997	56

The strength of each correlation is determined as zero (ρ=0), weak (±0.1-±0.3), moderate (±0.4-±0.6), strong (±0.7-±0.9) and perfect (±1).[317]

Figure 41 presents the data comparing the raw FIT scores with the IIN-% distribution for all participants.

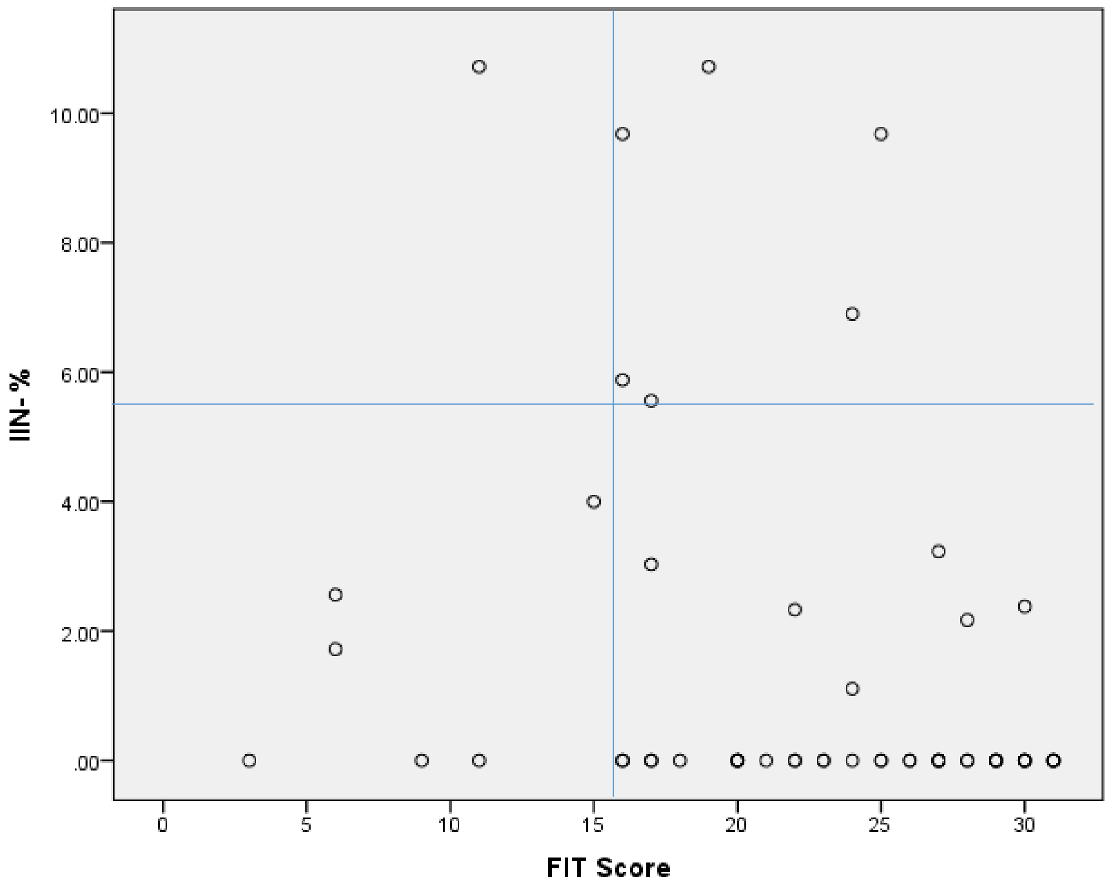

Figure 40 Scatter graph displaying the relationship between raw FIT score and IIN-% prominence in all participants.

Figure 41 shows a weak negative 'correlation' between the FIT and combined traffic light scores (n= 56, r_s= -0.340, ρ=0.010,). Although the Pearson's correlation identifies a weak negative correlation it is difficult to identify the trend from the scatter graph. This maybe because of the number of data points that scored high FIT scores and low prominence IIN-%. However, when the scatter graph is quartered a void area begins to emerge. The upper left quarter has a noticeable low number of data points. This indicates that participants that score low on the FIT test rarely show high distribution of approaches on not identifying the information. Furthermore, this void area does not correspond well with the value for the Pearson's correlation.

Figure 42 presents the data comparing raw FIT-1 scores with the combined traffic light scores.

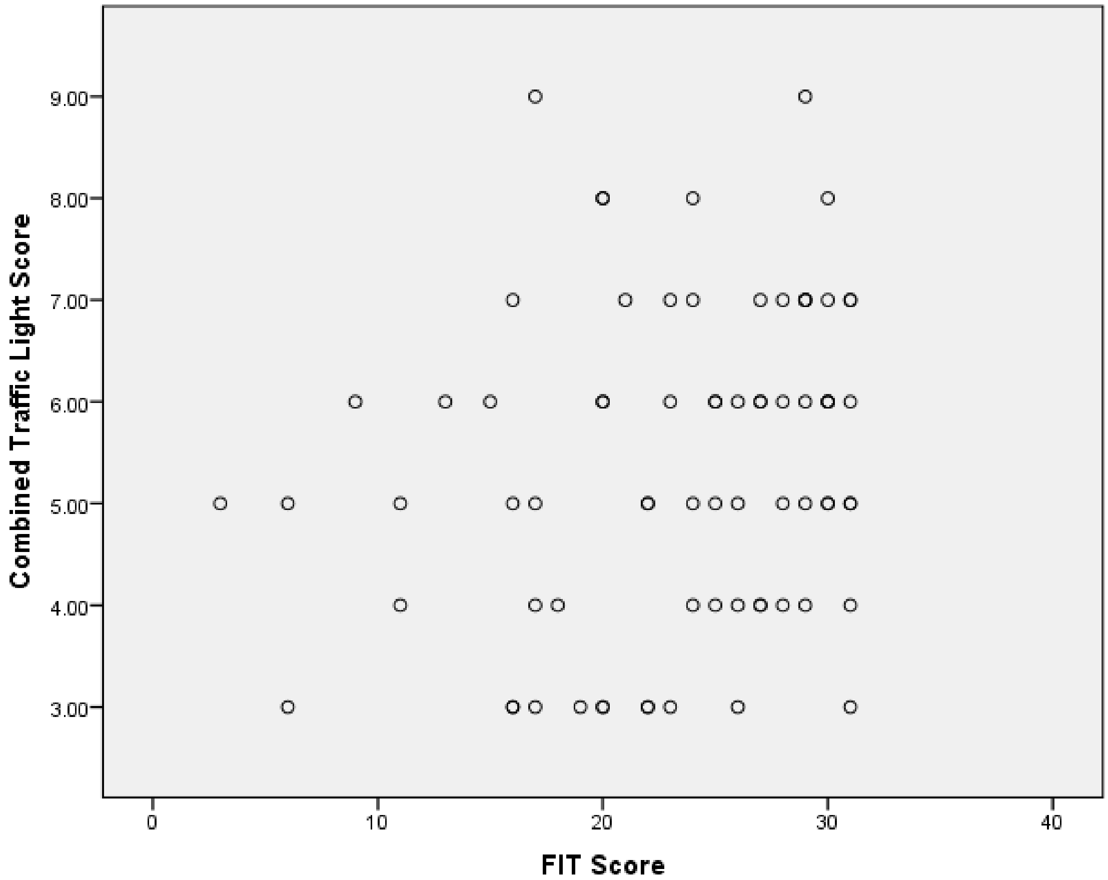

Figure 41 Scatter graph showing the relationship between raw FIT score and combined traffic light score.

Figure 42 shows no linear correlation between the FIT and combined traffic light scores (*n*= 74, *r*= 0.214, ρ=0.067, ns). Although the data does not show a significant correlation, it does highlight a void area where participants who score low on the FIT do not score high on the traffic light problem solving task. This void within the data set would suggest a threshold effect emerging from the data, whereby FIT scores can be used to identify participants who won't score high on open-ended problems, rather than being able to predict the success of all individuals. Therefore, the low FIT score could be used to identify individuals who need scaffolding towards more expert like behaviour.

5.2 GEFT Results

This section presents the results from the data collected using the GEFT test as identified in section 3.2.1. These results have been represented as raw score data as a histogram as seen in Figure 43, as calculated through the raw GEFT scoring method.

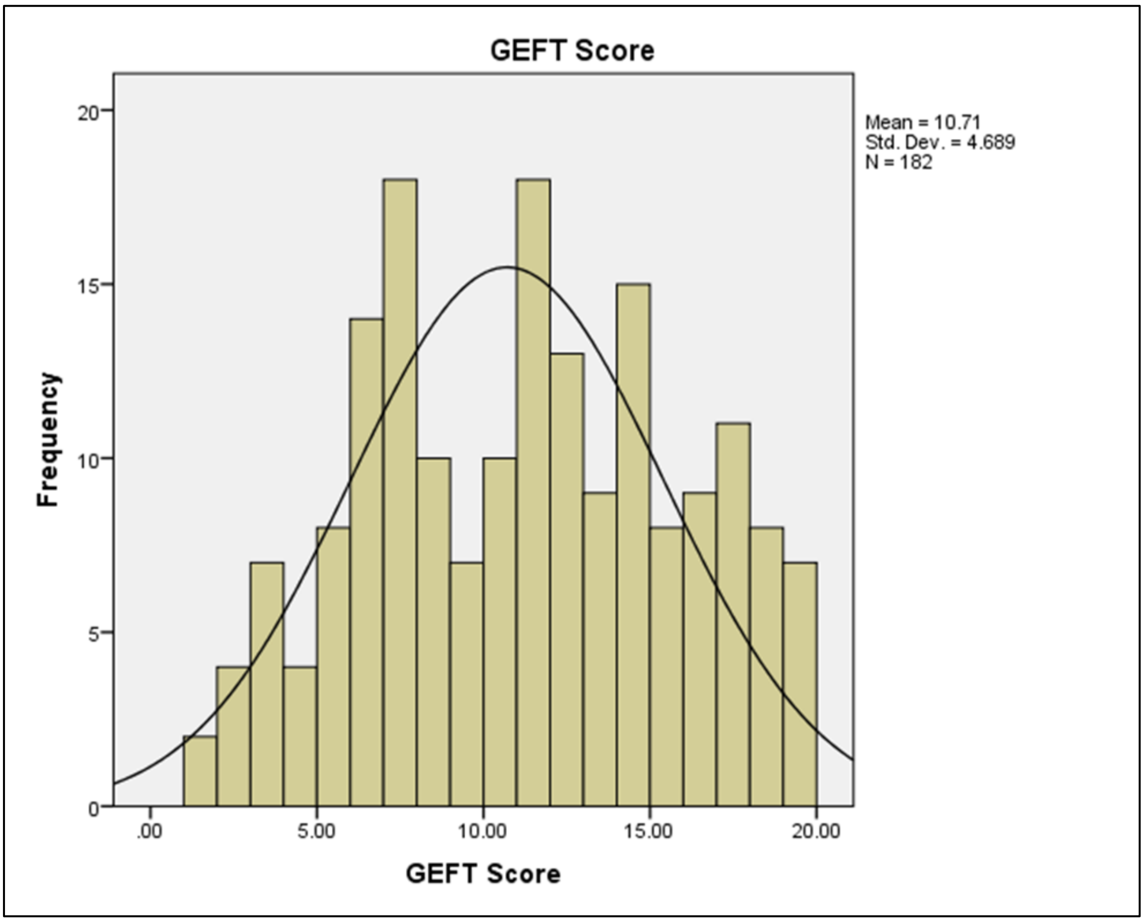

Figure 42 Graph showing the raw scores for the GEFT from all participants.

The processing of the data shows that participants showed mixed distribution, without participants showing particular bias towards low or high scores on the GEFT test (*n*= 182, *SD*= 4.689, *M*= 10.71, skewness = -0.028, Kurtosis = -0.951). As previously suggested, the GEFT is only an indicator of dis-embedding ability/ field independence rather than providing the full picture of field dependence/field independence.

The raw GEFT values for the participants who were involved in the qualitative study in section 2.1 were assessed for correlations against the percentage values for the occurrence of each qualitative code. The data was analysed using Pearson's Correlation where the data is assumed to be normally distributed and linear in nature. The data reported here are where there were some significant correlations on the Pearson's correlation test observed (Table 42).

Table 41 Pearson's correlation for GEFT scores against % distribution of approaches.

	GEFT Score		
	Pearson Correlation	Sig (2-tailed)	*N*=
GEFT Score	1	-	182
IIN+%	0.406**	0.001	62
A&E+%	0.179	0.164	62
ALG+%	0.167	0.193	62
EVA+%	0.201	0.118	62
IPF+%	0.008	0.951	62
DAS+%	0.187	0.133	66
NDIS+%	-0.205	0.099	66
LSA+%	0.407**	0.001	66
IIN-%	-0.396**	0.001	62
A&E-%	-0.202	0.115	62
ALG-%	-0.262*	0.039	62
EVA-%	-0.156	0.212	66
IPF-%	-0.146	0.257	62
DAS-%	-0.274*	0.031	62
NDIS-%	-0.024	0.855	62
LSA-%	-0.347**	0.006	62
CC+%	0.092	0.479	62
CCP-%	-0.050	0.697	62
CCA-%	0.073	0.574	62

The strength of each correlation is determined as zero (ρ=0), weak (±0.1-±0.3), moderate (±0.4-±0.6), strong (±0.7-±0.9) and perfect (±1).[317]

Figure 44 shows the relationship between participants' raw GEFT score and the percentage distribution of approaches used for IIN+.

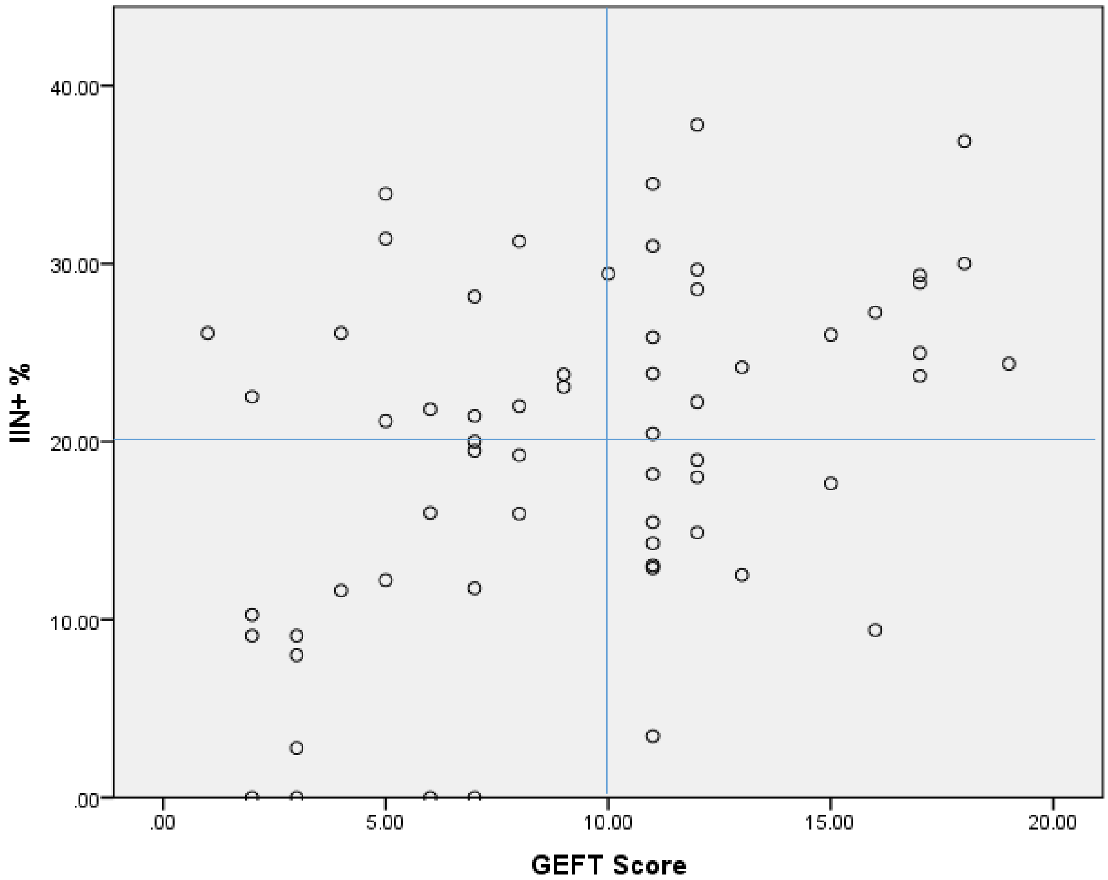

Figure 43 Scatter graph displaying the relationship between GEFT score and IIN+% prominence in all participants.

Figure 44 shows a moderate positive correlation between the GEFT score and IIN+% (n= 62, r_s= 0.406, ρ=0.001). This would suggest that a correlation maybe emerging between individual field independence scores and the percentage distribution of approaches spent on identifying the information needed.

Figure 45 shows the relationship between raw GEFT score data and the percentage distribution of approaches of LSA+.

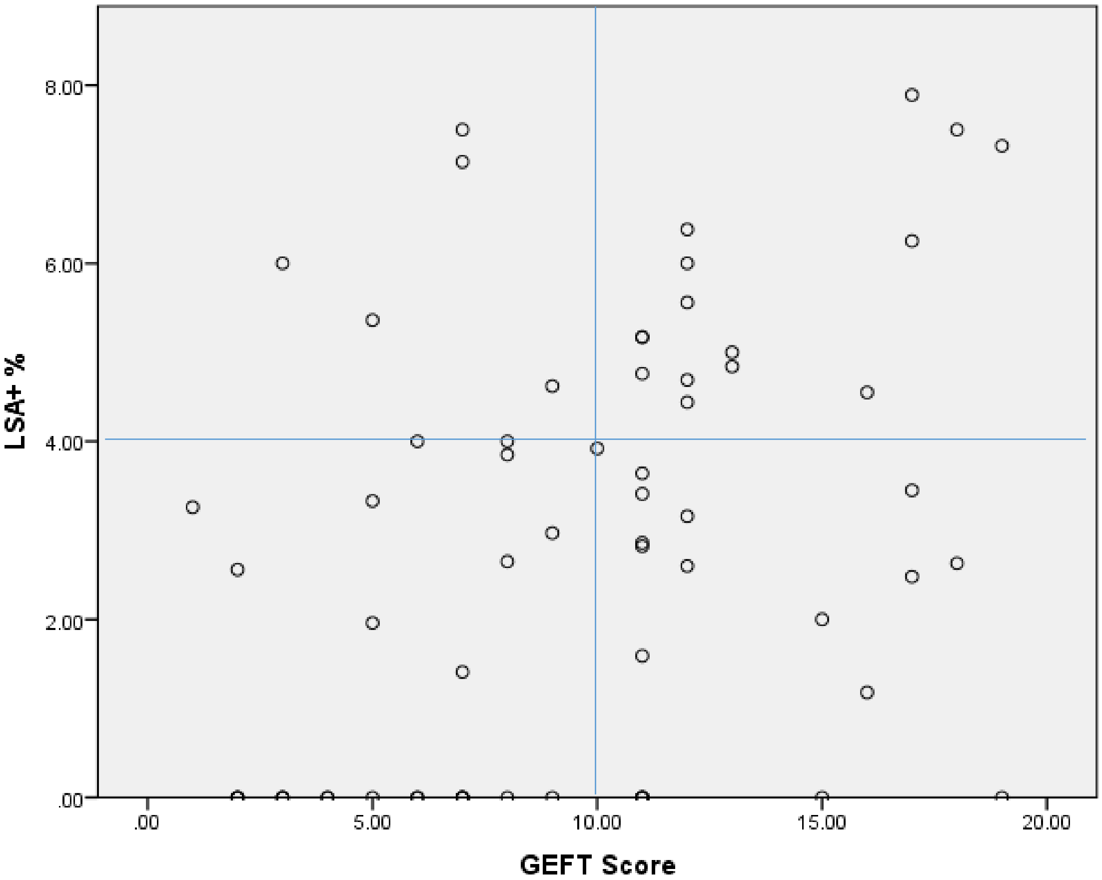

Figure 44 Scatter graph displaying the relationship between raw GEFT score and LSA+% prominence in all participants

Figure 45 shows a weak positive correlation between the GEFT and LSA+% (*n*= 66, r_s= 0.407, ρ=0.001).

Figure 46 shows the relationship between GEFT score and the percentage distribution of approaches for IIN- using a scatter graph.

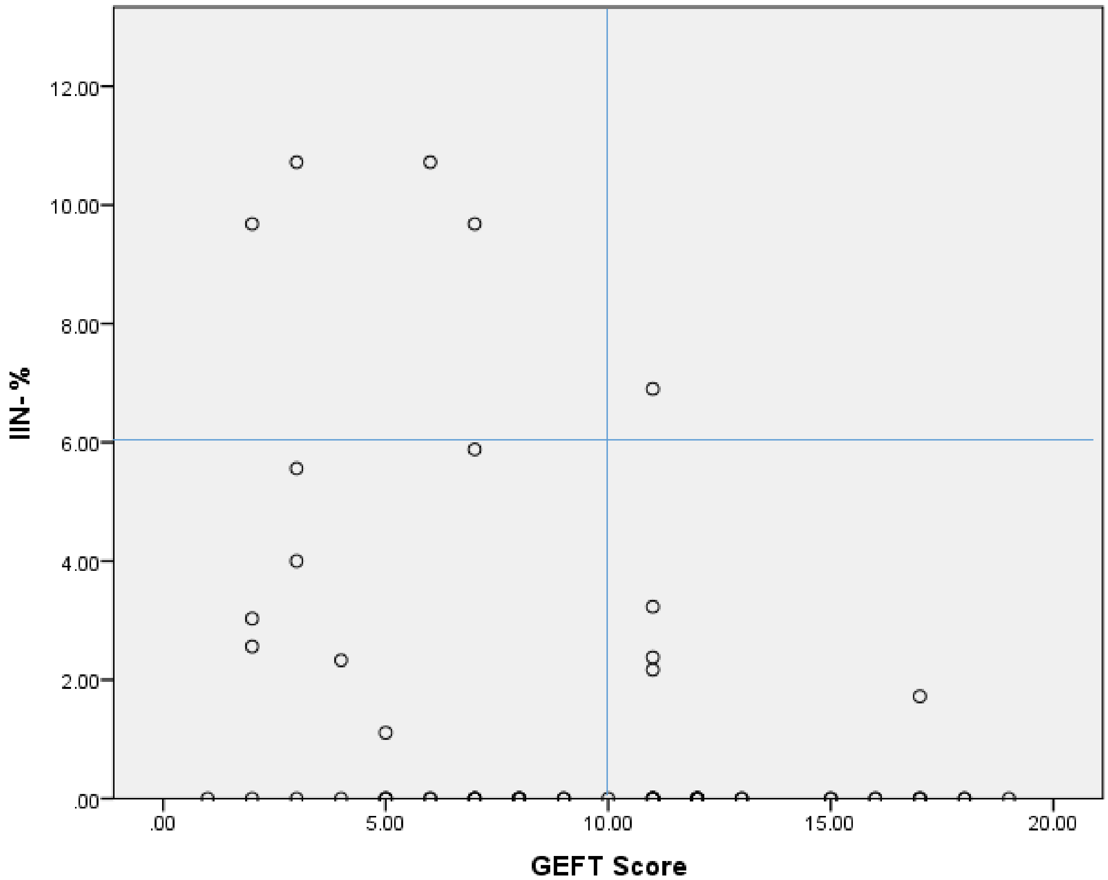

Figure 45 Scatter graph displaying the correlative effect between raw GEFT score and IIN-% prominence in all participants.

Figure 46 shows a weak negative correlation between the GEFT and IIN-% (n= 62, r_s= -0.396, ρ=0.001). What is interesting from this scatter graph is the upper right quarter of the chart area which shows that participants that have a high GEFT score do not show that they are unable to identify the information needed.

The scatter graph displayed in Figure 47 shows the relationship between GEFT score and ALG- % for all discipline participants.

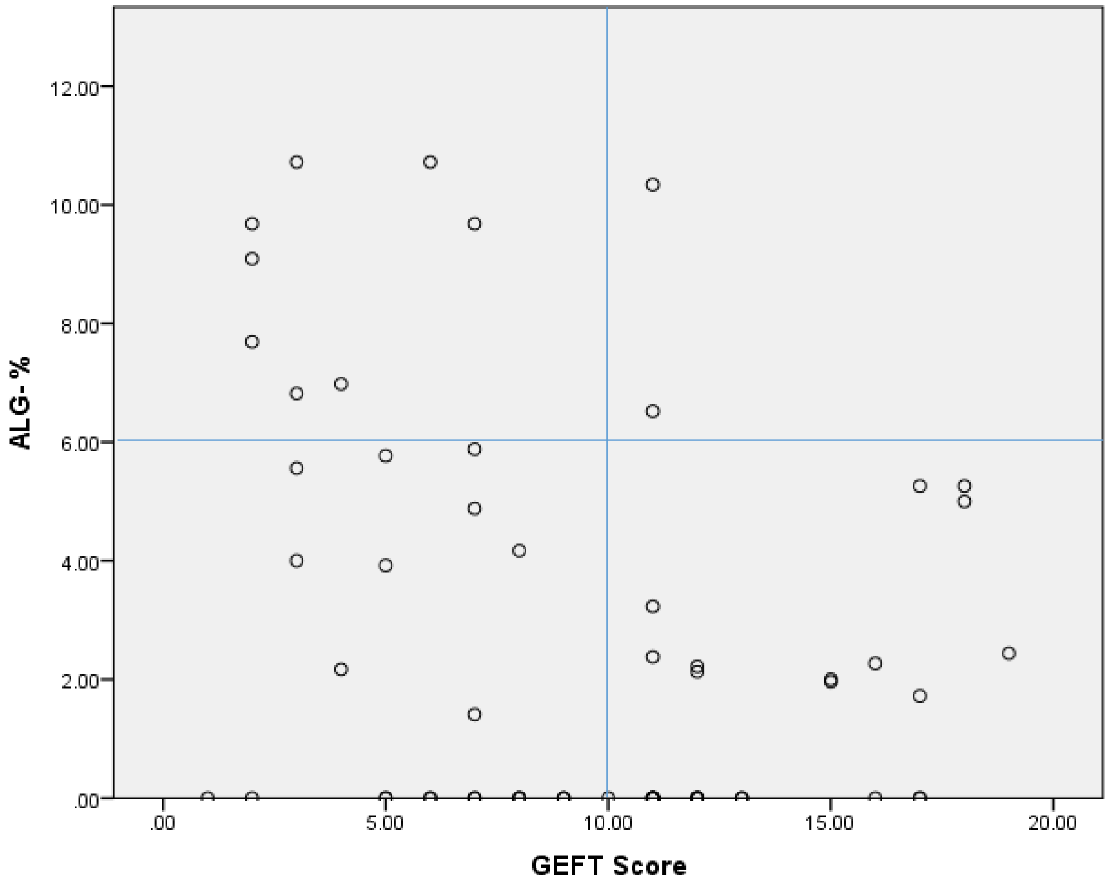

Figure 46 Scatter graph displaying the relationship between GEFT score and ALG-% prominence in all participants.

Figure 47 shows a weak negative correlation between the GEFT and ALG-% (*n*= 62, r_s= -0.262, ρ=0.039) showing that as participants score higher on the GEFT test they show lower prominence on the ALG-% distribution. The negative low correlation observed in Figure 47 is not as interesting as the emerging threshold effect observed in the upper right quarter of the graph. This quarter shows that participants that scored high on the GEFT do not have difficulty in making calculations or use algorithms and equations.

Figure 48 shows the relationship between the GEFT score and the percentage distribution of approaches for DAS- for all participants.

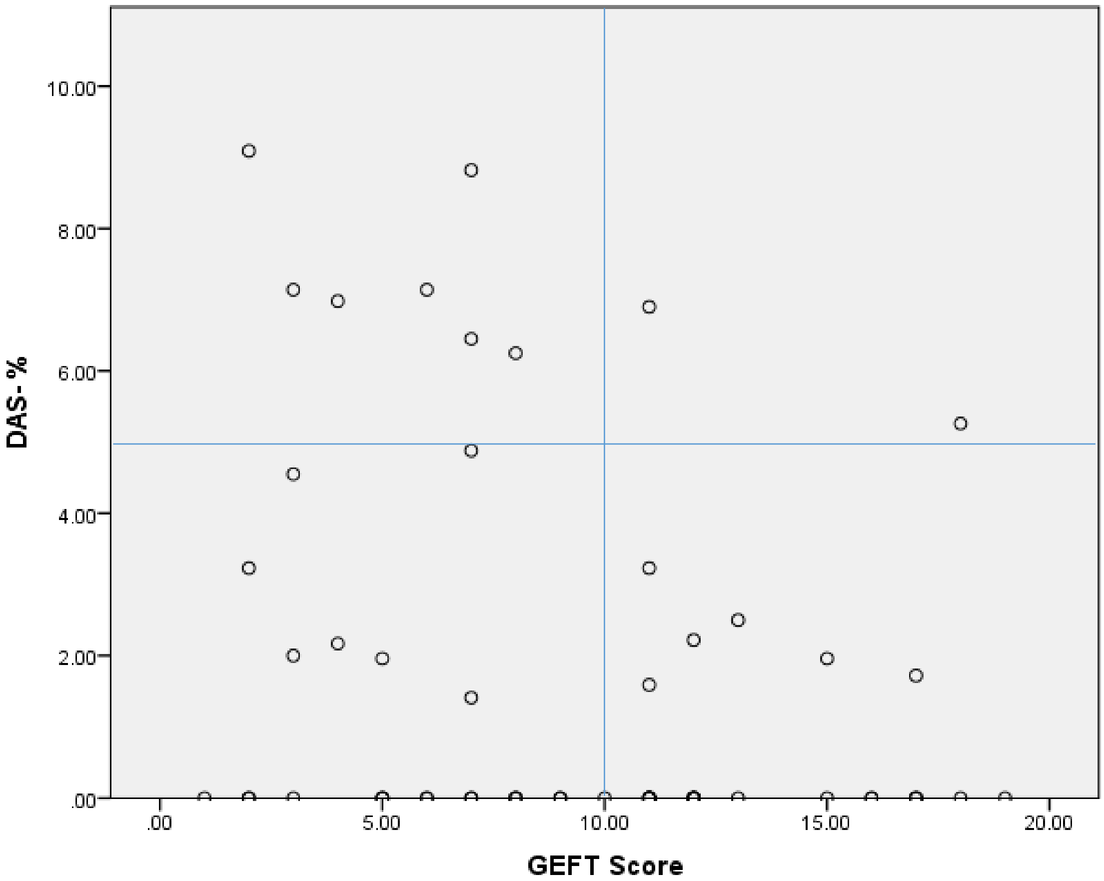

Figure 47 Scatter graph displaying the relationship between GEFT score and DAS-% prominence in all participants.

Figure 48 shows a weak negative correlation between the GEFT and DAS-% (n= 62, r_s= -0.274, ρ=0.031). The upper right hand side of the Figure 48 chart area shows a lack of data points which would suggest that participants who score high on the GEFT were unable to develop a strategy. This would suggest the field independence maybe a contributing factor in strategy development for open-ended problems.

Figure 49 is a scatter graph which demonstrates the relationship between GEFT score and LSA- %.

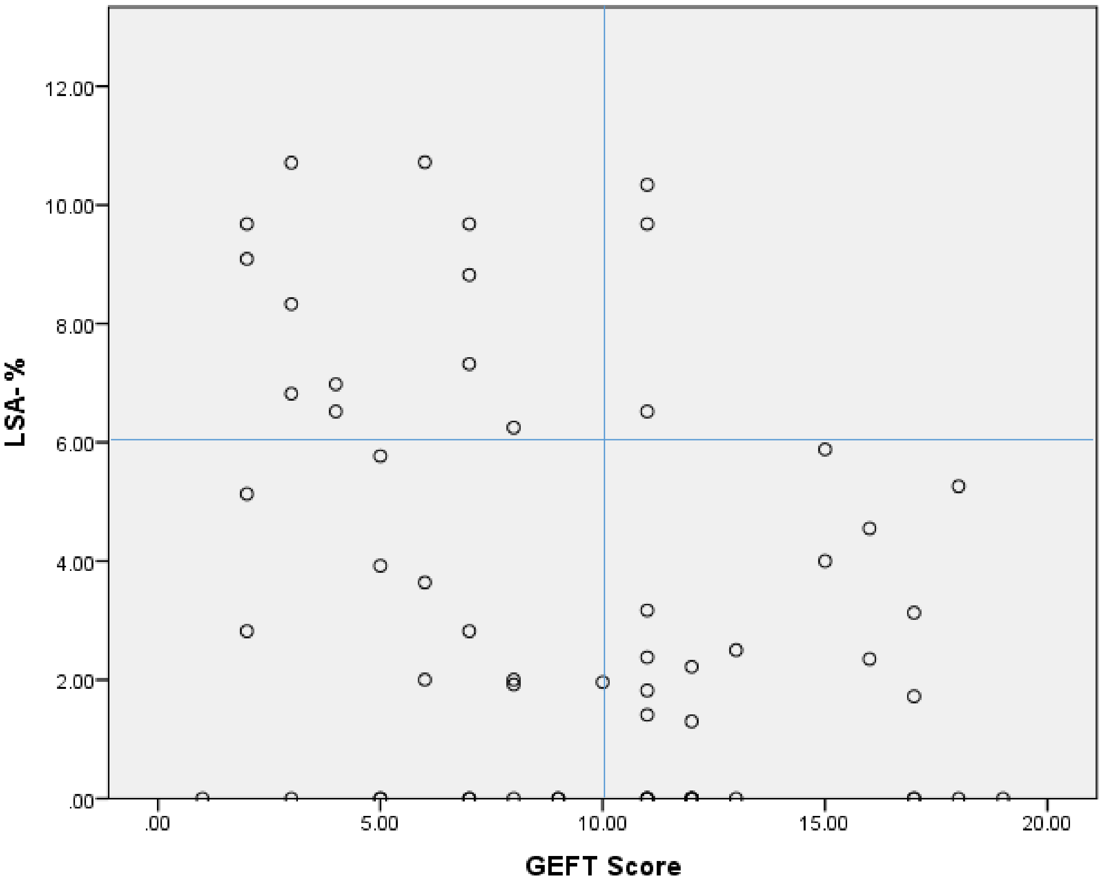

Figure 48 Scatter graph displaying the relationship between GEFT score and LSA-% prominence in all participants.

Figure 49 shows a weak positive correlation between the GEFT and LSA-% (*n*= 62, r_S= -0.347, *ρ*=0.006). Figure 49 shows that participants who score high on the GEFT lack the ability to apply a logical and scientific approach. This is shown by the lack of data sets displayed in the upper right hand area of the chart area.

Figure 50 shows the scatter graph displaying the relationship between GEFT score and combined traffic light score as described in section 2.8.

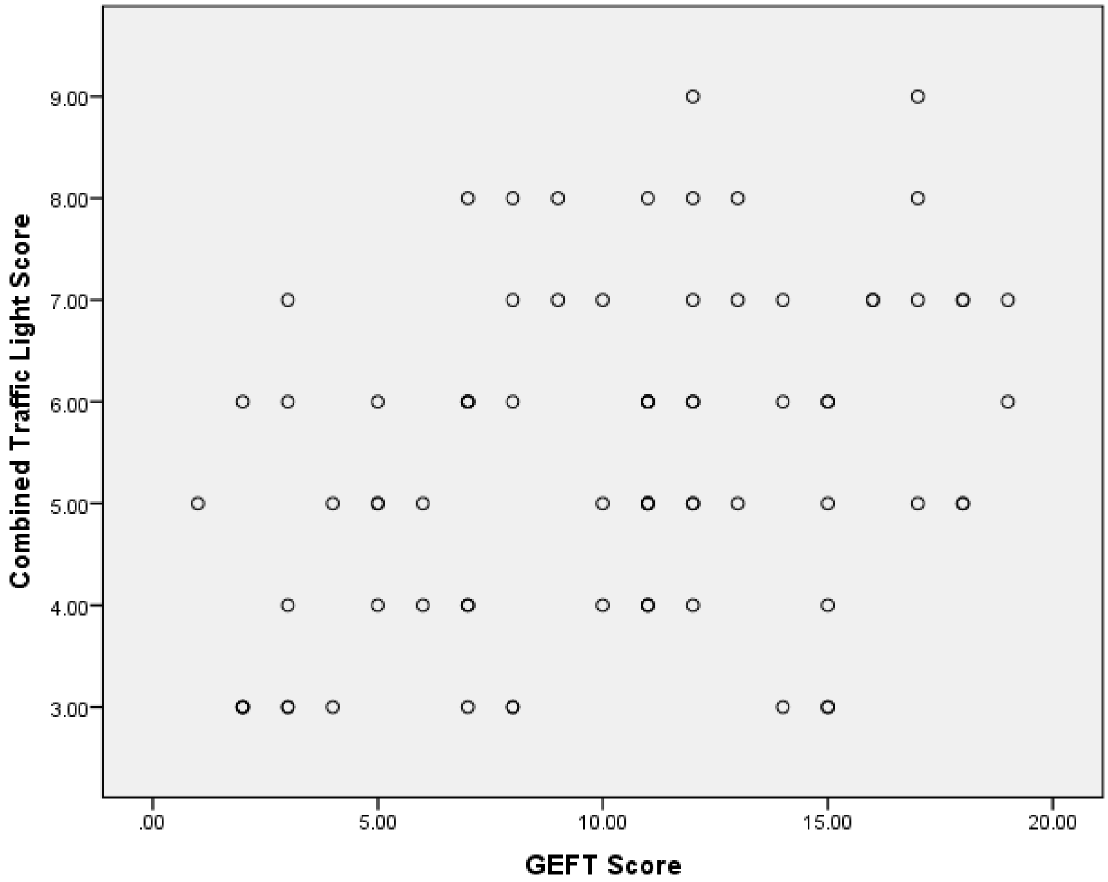

Figure 49 Scatter graph showing the relationship between GEFT score and combined traffic light score.

Figure 50 shows a weak positive correlation between the GEFT and the combined traffic light score (*n*= 79, r_s= 0.359, ρ=0.001). The Pearson's correlation score for Figure 50 would suggest the emergence of a linear correlation between scores on the GEFT and traffic lighted success score. However, the data plots appear to resemble a more oval profile rather than a linear one. What is also emerging in Figure 50 is that participants that score low on the GEFT test are unable to score high under the success criteria outlined in section 2.8. Furthermore, participants who score a high traffic light score generally have a high GEFT score.

3.2.3 GEFT vs FIT

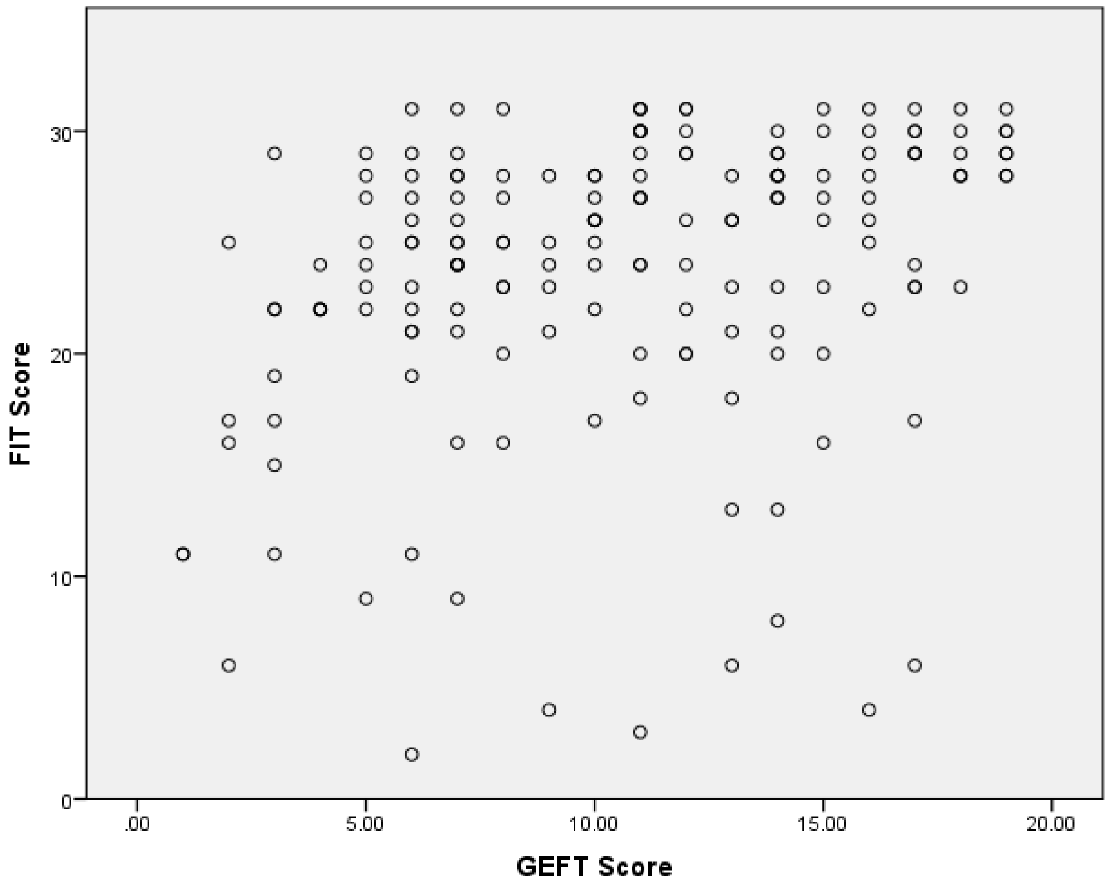

Figure 50 Scatter graph displaying the relationship between FIT-1 score and GEFT score.

Figure 51 shows a weak positive correlation between the FIT-1 score values for the FIT and GEFT score (n= 172, r_s= 0.374, ρ=0.000). Figure 51 suggests that most individuals score high on the FIT as previously identified in Figure 40. However what is emerging from Figure 51 is that generally participants can achieve a wide range of scores on the GEFT whilst still maintaining a high FIT-1 score. This means that participants can have the ability to hold a large quantity of information, as demonstrated with their M-capacity, but may lack the ability to dis-embed the information, as identified through the field independence ability.

6 Discussion

The investigation into the approaches used by STEM undergraduate participants has indicated possible reasons for success in answering open-ended problems, and the limitations of the approaches used. The qualitative methodology used revealed approaches that would not be revealed using a quantitative methodology. This chapter will discuss the approaches used by participants and their inevitable implications for teaching. The chapter will further discuss psychometric profiles and how these related to the approaches used by participants.

6.1 Approaches Observed and Codes Developed

Reliability is as important for qualitative research as it is for quantitative research.[318-320] It is important that the codes developed were consistent across different coders (people who develop the codes), and raters (people who use the codes),[321, 322] and that the codes were applied consistently. To ensure that the measuring instrument was 'valid' three separate criteria must be considered by the qualitative researcher: stability (does the coder's use of the codes change over time), accuracy (comparison of the study's set of codes against other coding schemes) and reproducibility (do different coders code the same data in the same way).[323] This section will focus on the accuracy and the reproducibility of the codes.

Accuracy

There are many models associated with the different approaches used when answering problems.[146, 156, 157] The general consensus is that problem solving must be a multi-stage process. During this study nine different themes were observed emerging from the think aloud problem solving sessions with the chemistry and physics participants. No new themes were observed emerging from the data from subsequent disciplines and so the emergent themes were considered to be saturated. The themes observed were:

- Identifying the information needed (IIN±)
- Approximation and estimations (A&E±)
- Algorithms (ALG±)
- Evaluation (EVA±)
- Identifying and framing the problem (IPF±)
- Developing a strategy (DAS±)
- Not distracted by the details (NDIS±)
- Logical and scientific approach (LSA±)
- Confident and no confusion (CC+/CCP-/CCA-)

The emergent themes from this study were similar to those observed in previous studies. Polya suggested that there were four discrete stages that an individual most go through to be successful at answering problems.[156] These four stages are understanding the problem (IPF+), developing a plan (DAS+), implementation of the plan (LSA+) and then reflection and evaluation (EVA+). These four stages are seen emerging from the data of this study. However, as stated by Bodner, the stages of problem solving as a linear process is overly simplified and the approaches appeared in a more chaotic order than suggest by Polya.[156, 324, 325] The evidence from this study suggests that solving open-ended problems always starts with an 'understanding and framing the problem' stage. However, the processes that follow are considerably less linear than suggested by Polya[156] and more chaotic than suggested by Bodner.[324] Many of the participants employed approaches that involved 'identifying the information needed' throughout their solution, continually adapting their plan and approaches when they encountered problems. Overton and Potter identified eight different approaches from their data obtained from a study of similar problems:[316]

- Makes estimations, approximations, generates data
- Understands the problem, what they need to know or do
- Logical approach and reasoning
- Makes sensible assumptions
- Evaluates answers, aware of limitations
- Seeks an algorithmic approach
- Distracted by context of the problem
- Lack of knowledge is a barrier

As can be seen, the approaches observed are very similar in both of these studies, which suggests that the coding schemes were accurate for analysing approaches used during open-ended problem solving. Few models of problem solving have accounted for the participant's confusion with the problem and the lack of confidence in their own abilities. Even the phenomenographic study by Walsh *et. al.* did not report confusion or lack of confidence. [326] This was surprising as with more algorithmic type problems the impact of self-confidence, perseverance, motivation, belief and value are well documented.[243, 327] Although in our study lacking confidence in their ability and becoming confused by the problem emerged frequently, it could be considered more of a behaviour than an approach. This may be why other studies of problem solving have not considered reporting the behaviour when developing their models.

Reproducibility

This study focused heavily on the reproducibility of the data because the study involved comparisons between data sets from different disciplines, with much focus placed on the inter-rater reliability. Inter-rater reliability has been well documented as a triangulation method for validating codes for qualitative research. However, it is not as well documented with regards to being used to analyse semi-structured interviews, which these think aloud sessions could be considered. Furthermore, many publications have failed to report whether they conducted inter-rater coding, especially with interview data,[328-332] or have provided sketchy and ambiguous details on how they used inter-rater coding.[333-335] It has been suggested that the reluctance to demonstrate test reliability for qualitative coding is because of mistrust in the process of using inter-rater coding, as the terminology can have multiple meanings and there is no agreed ‘canons’ regarding qualitative data analysis.[336-338] Presently, little research exists that discusses the reliability of coding schemes for semi-structured interviews, and therefore expertise have to be drawn from other qualitative data types such as field notes,[337] documents,[323] survey data[339] and extended interview discussions.[340, 341] Using guidance from these sources robust inter-rater coding was established as shown in Table 12 and Table 13. The coders all had previous experience in coding qualitative data, but had not had access to all the data within this study. There is discussion in the literature of whether it is best for a group of coders to work together to develop a bank of codes and, therefore, agree before coding, or work independently using an already defined bank of codes to ascertain agreement with their definitions.[342, 343] The coders in this study decided that the independent coding approach would be more robust. The coders agreed 85% of the time, and upon further discussion the definitions of some of the codes were refined, in particular where discrepancies existed in EVA and LSA. Furthermore, one coder was reluctant to assign codes in many instances, which was in part because they were unable to define passages as discrete codes. This is a well-documented issue with open-ended response coding where, unlike closed response answers, certain passages might require multiple codes.[338]

Code Reliability based on question order and question type

Some chemistry undergraduate participants were presented with the same questions as the other chemistry undergraduate participants but with the questions in a different order (*n*=5). For the purposes of this discussion participants that were presented with the questions in the original order will be referred to as SET1 and those participants who received an alternative order for the questions will be referred to as SET2. The profiles for SET2 participants, for a majority of cases, were very similar to those in SET1, showing prominences along IIN+, ALG+ and IPF+ as demonstrated in Table 14. Although the proportions of these codes may be slightly different between participants, the overall shape of the profile was similar. Furthermore, the individual participants in SET2 displayed a very similar profile shape to the overall discipline profile shape. Figure 19 shows the overall profiles of SET1 and SET 2 participants. What can be further observed in Figure 19 is prominence of CCP- with both SET1 and SET2 participants. The prominence of the CCP- code in both sets suggested that no matter which order the questions were presented the level of confusion and lack confidence with the problem is similar.

With the exception of one individual, the majority of participants showed a profile which was similar to the overall discipline profile observed in Figure 18. This would suggest that question order has no impact on which approaches are used most when students solve these types of problems. The impact of question order on success could not be evaluated because of the small sample size of SET2.

Some physics undergraduate participants (*n*=5) were presented with a different set of questions. For the purposes of this discussion participants that were presented with the original set of questions will be referred to as SET3 and those participants who answered the alternative questions will be referred to as SET4. The individual profiles for the participants in SET4 were similar to those in SET3, displaying the same three prominent codes of IIN+, ALG+ and IPF+, as shown in Table 15. What is slightly different for participants in SET4 is that the individual radar profiles in Figure 20 and Figure 21 showed greater proportional distribution towards ALG+ than the profiles in SET3. This may indicate that the participants in SET4 felt these questions required more calculations and use of algorithms than the participants in SET3. Although there was a slight shift in proportions of where the approaches are emerging, Figure 23 showed that the overall shape is similar. This was further supported by the proportion of negative coded approaches which showed CCP- as the only prominent code.

Figure 20 and Figure 21 clearly showed that all participants in SET4 had very similar profiles to each other, with all but one participant showing ALG+ as the highest percentage distributed code. Despite these differences, the overall SET4 profile in Figure 23 showed that despite slight shifts in proportional prominence of the codes, the same top three codes were emerging and no additional approaches were emerging from the data due to participants being asked a different set of questions. This means that we can be sure that the bank of codes emerging from the data are the complete set of codes required to analyse open-ended problems irrespective of the questions presented to the participants.

6.2 Approaches Exhibited by Physical Science Undergraduate Participants

As the introduction demonstrated, there are vast amounts of literature in the physical sciences that looked at problem solving and, in particular, methods and interventions to improve performance. However, very little literature investigated what students were doing when they engage with problems, especially analysed through a qualitative framework.

Identifying the information needed was a prominent approach emerging in a majority of participants solutions. When participants identified the information required they focused on acquiring numerical values to use later in an algorithm. This was seen in studies by Overton *et. al.*,[316] and Walsh *et. al.*[326], although these studies didn't identify the information needed as a separate approach from identifying and framing the problem or making approximations and estimations. Overton *et. al.* stated that participants that were successful at solving problems should be able to 'generate their own data,' but did not state whether this included identifying the information needed in order to answer the problem or whether this solely related to making approximations and estimations. The presence of 'identifying the information needed' revealed that participants in our study acknowledged that they needed additional data to solve the problem. Participants exhibited high levels of the IIN+ approach which showed that they preferred to ask for the information rather than make estimations. This was indicated by a majority of participants who used very low levels of A&E+, but high levels of IIN+. The Overton *et. al.*

study used an umbrella code for making estimations, approximations and generating data.[316] The umbrella code proposed by Overton *et. al.* may have encompassed the code from our study for identifying the information needed (IIN), however Overton *et. al.* did not specify whether this were the case. Our study clearly identified a separation between IIN and A&E approaches, and as such they were coded separately. Although many occurrences of IIN+ appeared alongside identifying and framing the problem, some of the occurrences for IIN+ emerged once the participant had clearly chosen their strategy to solve the problem. This can be seen in the following examples:

> "*Well first it will depend on the size of the venue. So can you tell me how big that is?"*

As can be seen in this example the participant was unsure about the information they had been presented with in the problem and were asking for additional information. Although this could be viewed as a framing of the problem (IPF+) the participant asks specifically for the size of the venue to support the development of their strategy.

> *"I could find out the volume. So… can you tell me the radius of the earth's atmosphere?"*

In this example the participant was already working with a clearly defined strategy to use PV=*n*RT and wanted to calculate the volume of the atmosphere and asked for a specific piece of information so that they are able to continue with their chosen strategy. This example for the IIN+ approach showed that participants were using it even once they have commenced a strategy through identifying and framing the problem. This clearly showed that identifying the information needed was a separate code from identifying and framing the problem in physical science participants.

Many of the participants identified strategies that required the use of algorithms or calculations (ALG+). The use of specific data and asking for equations manifested in some participants as a result of searching for a suitable strategy, but also once their strategy had developed. The emergence of high use of ALG+ will not surprise many researchers, who have suggested that seeking an algorithmic approach is common in novice problem solvers.[152, 344, 345] This has been observed in other qualitative studies investigating problem solving, in particular Walsh *et. al.*[326] and Overton *et. al.*[316] who suggest that seeking an algorithmic approach indicated a less structured approach, because the participants relied on calculations, failed to evaluate, and struggled to think of variables beyond those observed in the question. This was evident in many of the chemistry participants in our study, who despite struggling to use PV=*n*RT because of the lack of data, remained committed to this particular strategy. However, our study has indicated that the stricter definitions of expertise by Walsh *et. al.* may not reveal the whole story. Although it is true that many participants depend upon the algorithmic approach to solve problems that suggest a numerical answer is required, participants were still able to achieve success depending on how well they framed the problem, and whether the additional data identified fitted the problem. That is to say, although seeking an algorithmic approach may not produce success at open-ended problem solving all the time, it by no means results in unsuccessful problem solving. There was a further difference between our study and the Overton *et. al.* study. In the Overton *et. al.* study, the code for algorithms focused on participants 'seeking an algorithmic approach,' identifying the behaviours used by their participants whilst answering the problems. This was different from our study which identified the uses of algorithms, focusing on the mechanical implementation of algorithms as an approach rather than the behaviour of seeking algorithms. For example some of the ALG+ codes in our study identified participants using $PV=nRT$, $\rho=m/v$, $C=2\pi r$ and $V=4/3\pi r^3$. In addition to identifying the use of algorithms, the ALG+ code in our study identified the implementation of algorithms through calculations made by the participants, including basic addition, multiplication and division. However, this was only coded where it was written in the script or verbal stated by the participant and not from assumed calculations. This means that all the calculations that a participant made may not have been captured because they preferred to make them mentally rather than stating or writing them down. This may mean that participants in the physical sciences used far more algorithms and calculations than we are currently aware.

Both chemistry and physics participants mostly lacked evaluation (EVA+) skills and when they did evaluate it tended to be superficial. For example "*oh no why did I do that?*" Although this could be considered evaluation there is no further action taken by the participant. This would therefore not be categorised as meaningful evaluation. A further example is

> "*cause I was thinking it would just be one rotation of like the tyre, just, I don't know, it seems like it would sort of make sense."*

In this example the participant makes assumptions. However, they do not supply supporting arguments about why they believed one rotation would be sufficient. These examples are representative of all participants' individual approaches for EVA+. When compared against the definitions of problem solvers by Walsh *et. al.*, it was difficult to establish how meaningful Walsh required evaluation to be in order to identify it as an approach.[326] This creates a dilemma because Walsh *et. al.* suggested that evaluation is essential for employing a scientific approach.[326] However, our study has identified that evaluation is not necessarily required to be successful at problem solving. When the results in Table 14 and Table 15 and the traffic light data in Table 29, are compared many participants were still able to score green solutions despite a lack of evaluation. One participant in our study was different from the others. Participant UHULLPH3 used more evaluation than other participants from the undergraduate physical sciences, although this greater use of evaluation is not reflected in their success at solving the problem.

Identifying and framing the problem emerged in our study as a very important code for physical science participants, and appeared to act as a central node for developing a strategy, as suggested by Camacho *et. al.,*[346] Chang *et. al.*[347] and Kim & Hannafin.[348] Camacho and Good identified 27 characteristics for successful and unsuccessful problem solvers. Two of those characteristics would fall under our umbrella term identifying and framing the problem. Camacho and Good stated that to be a successful problem solver participants need to "*reread the objectives on the problem card before starting the solving process*," and, "*to perceive and think and the problem as a task of reasoning and development of a solution.*"[346] Although both of these terms fit under the IPF+ approach in our study, Table 14 and Table 15 show that chemistry and physics participants used the approach throughout their strategy and not just towards the beginning. The studies by Chang *et. al.*[347] and Kim and Hannafin[348] reported that exploration of the problem was important when students engage with problem solving. In our study all the individual participants, to some degree, used additional framing of the problem before they could develop a meaningful strategy instead of relying on the question parameters as they were presented. This approach emerged not just on its own, but in combination with IIN+, A&E+ and ALG+. This was because physical science participants were seeking to find a numerical value that they could anchor their strategy to, such as the number of people attending a music festival, or asking for the density of the atmosphere. This is seen in participant UHULLCH10 who in question 2 states,

> "*Do you know how much is worn per mile?... Do you know how many layers there are or not?... What other information is known about the tyres?... Do you know the depth of the tyre?*"

The participant bombarded the interviewer with a series of questions about specific pieces of information they thought they required. Interestingly, this participant was asking for the right information required to solve the problem, but was unable to find the values they thought would anchor their strategy. They were also unable to identify the separate stages required to solve the problem, instead trying to complete the process through a single step. This behaviour was observed in solving closed problems in a study by Frazer and Sleet[190] who were investigating problems that involved calculations and breaking the problem into subsections. In their study they observed that, despite participants being able to solve the sub-sectioned problems, they were unable to answer similar questions when they weren't sub-sectioned. Frazer and Sleet suggest that this disparity was due to participants being unable to develop a clearly defined strategy or frame the problem.[190] However, the greater success at solving sub-sectioned problems may be due to less cognitive overload, whereby participants who were unable to answer the normal problems experience cognitive saturation. When the problem was sub-sectioned the participants required less framing because it was already done for them.[190] In our study the problems were not sub-sectioned. This might suggest the abundance of incidents of participants identified and framed the problem happened because there was little guidance provided in open-ended problems. Identifying and framing the problem has emerged in other studies including Overton *et. al.*[316], Walsh *et. al.*[326] and Bodner.[324] Although all these studies identify a planning component as integral to developing a successful strategy, our study has suggested that it is required to be successful but not an indication of success. That means that it is just as likely to have emerged in successful and unsuccessful problem solvers as defined through traffic lighting in section 2.8. Bodner suggested that the stages of solving problems were non-linear requiring constant revision as they materialise.[324]

For the most part participants in the physical sciences were able to successfully develop strategies (DAS+), and as Table 14 and Table 15 show only one participant was completely unsuccessful at developing a strategy for open-ended problems (DAS-). Participant UHULLCH5 (SET2 member) was able to develop multiple strategies when solving their problems, and in particular for problem 2. In this example the participant chopped and changed their strategy three times. This showed successful use of the think aloud process, as this was not apparent in their solution script. Furthermore the participant uses multiple strategies when solving problem 3. Developing multiple strategies was also observed in SET4 participants from physics. An example of this is observed in participant UHULLPH10 who used up to four different strategies with a single problem. However, instead of the participant using multiple strategies to justify their answers, multiple strategies reflected more the participant struggling to develop a suitable strategy. Camacho and Good state that to be a successful problem solver participants needed to "*not use trial and error*," and, "*to use a knowledge development strategy*."[346] Our study cannot fully support those claims. Some participants, as stated earlier, used multiple strategies to answer the problem, some of which used trial and error approaches. This is interesting as Camacho and Good state that "*knowledge of more than one method or principle to solve the problem*," is a characteristic of a successful problem solver.[346] In our study participants used trial and error strategies in order to familiarise themselves with the problem. As such, participants were not assessed just on their first attempt, but over the whole period they took to solve the problems. This meant participants had the opportunity to try one strategy, and then change to an alternative strategy if it wasn't successful. This could be considered a trial and error approach, which our study found no link between success and unsuccessful solutions.

Physical science participants become distracted by the lack of information in the problem. Table 14 and Table 15 shows that very few chemistry and physics participants were not distracted by the lack of information throughout their problem solving (NDIS+) it was not as prolific as in other disciplines and only one participant showed prominence for this approach (UHULLCH6). This would suggest that, although the approach may have some impact, it was not a major influence on their overall approaches. An example of being distracted by the lack of information can be seen in participant UHULLCH9 who stated "*is it including everything though? Everything structurally wise and…*" This comment followed the participant asking the interviewer what the question was asking. The perception of the participant was that mountains, buildings and trees would significantly alter the volume of the atmosphere, and therefore effect their calculations. The participant highlights another area they are confused with later in their solution stating

> *"so I need something that will change decimetres to the minus three. That would get rid of if completely… I'm just going around in circles… It's an unknown quantity so… change it."*

This example showed that the participant does not have a piece of information they think they need and, furthermore, was struggling to see past this limitation. Eventually, the participant reconciles their discomfort and is able to continue with their strategy, but it resulted in a stalling of their strategy. Overton *et. al.* state that some participants can become distracted by the context of the problem and their own prior knowledge.[316] Our study would agree with this statement. Overton *et. al.*, however do not state whether participants in their study were able to overcome their distraction, or whether the distraction limitation was fatal to their solution. In our study, chemistry and physics participants, for the most part, were able to overcome their distraction and successfully provide a solution.

Table 14 and Table 15 show that participants in physics show more logical and scientific approaches than chemistry participants. Thirteen participants in physics were able to show logical and scientific approaches on all three problems whereas no chemistry students showed the same. Furthermore, four participants in chemistry were unable to show a logical and scientific approach for any problems; this change may reflect or be responsible for the different success scores observed between the physics and chemistry participants (Table 14). This approach was really the only approach observed that showed a difference between physics and chemistry participants.

Physical science participants became confused with the problem and lacked confidence in their ability (Table 14 and Table 15). Examples of becoming confused with the problem are seen in participant UEDINPH5 who states that they,

> "*don't know whether I'd need any more information*," and, "*I was going to do like four times the number of people divided by like how long… I don't know if that's right*."

In both these examples the participant was struggling with the parameters of the problem. In the first example the participant was unsure whether they had acquired the correct or sufficient information resulting in them hesitating with proceeding with the problem. The comment from the participant is followed by prolonged silence. The second example for the participant showed that having made some calculations, they become confused with how to continue the process. An example from chemistry can be observed in participant UHULLCH8 who states, "*I'm trying to get it down to, as, like so it should if it gets to. I don't know. I'm just sort of seeing trying to get this equal to that."* In this example the participant was struggling with uncertainty in their strategy. The participant was prompted to reflect on the calculations they had completed and became confused with what they had done and how they wanted to proceed. Table 14 and Table 15 also showed that participants struggled with their ability. An example of an individual lacking confidence in their ability is seen in participant UHULLCH7 who states "*this is a bit unfair I think were stemming into physics territory, ah I'm trying to think of my Physics A2 now.*" In this example the participant lacked confidence in their ability, assuming the problem was based around physics concepts rather than assuming they could use principles they understand. Crucially, our study differed from studies by Camacho and Good, Overton *et. al.* and Walsh *et. al.*, because some participants who were confused by the problem and lacked confidence in their ability were still able to become successful at solving problems.

The individual profiles presented in Figure 16 through Figure 23 show that approaches used by students studying physics and chemistry look very similar, with pronounced elongation in the IIN+ code (identifying information needed) and along the ALG+ code (algorithmic: using equations and calculations). Despite the profiles and behaviours of these participants being very similar there were differences in the success for each discipline (Table 27). Both chemistry and physics participants showed similar success when answering question 1 which was non- domain specific. However, once the questions required scientific understanding, the disciplines diverged. For both question 2 and question 3 physics participants had the greater success. One possible explanation is that physics undergraduates were more comfortable with the mathematics required to answer these problems. However, as discussed previously, the interdependency of approaches during the framing stage is more complicated than previous research suggested. Few chemistry participants achieved the same traffic light score for all questions. If discomfort with mathematics was the main cause of low traffic light score then it would be expected that the scores for all the problems would be low. However, this cannot be the case because chemistry participants scored a range of traffic light scores for the questions. An alternative explanation is that physics students are more accustomed to developing models, be that through drawing diagrams (observed in some participants in our study) or mental concept models. The implication here is that physics participants are able to develop more meaningful problem framing and execution of a strategy than the chemistry participants because of a combination of enhanced maths and model building ability. This would account for similar approaches emerging from the data, but different levels of success. This would mean that physics undergraduate participants are operating in Walsh *et. al.*'s scientific approach or structured plug and chug approach despite high levels of evaluation not being observed in physics participant profiles.[326] Our study would not suggest that physical science participants are operating at an expert level defined by Walsh *et. al.*[326] or by Camacho and Good[346] despite some participants showing greater success than other participants (Table 27). This is because there was still too greater reliance on the use of algorithms and initial problem framing stages, and participants were unable to evaluate their solutions in a 'meaningful' way and take action following that evaluation.

There was one participant whose individual profile was dissimilar to those of the other participants. Participant UHULLCH6 showed a wide range of approaches, all with similar distribution; there was a retraction along the IIN+ and ALG+ codes, and elongation along the IPF+ code and NDIS- code (participant became distracted by the details of the question). The participant was showing characteristics which Overton *et. al.* described as transitional, with the participant showing a mixture of positive and negative approaches.[316] This is reflected in the transcript of their pencast, whereby the individual frames what needed to be done, but was unwilling to commit to using calculations in their strategy instead making assumptions. The participant shows this by stating

> "*because I'm making an estimation about how far a car can travel before that one atom layer from the tyre would be removed… so I'm just assuming that one atom layer would be in 10kilometres*."

Participant UHULLCH6 asks for less data than other participants and is further distracted by the lack of data provided which hindered them developing a strategy. This participant also fitted well with the ‘No clear approach’ definition of Walsh *et. al.* whereby the participant was unable to sufficiently analyse the situation based on the given variables to adopt a clear scientific approach to solving the problem.[326] Walsh *et. al.* suggested that participants who exhibit these approaches are unable to discuss the science in terms of concepts, and were incapable of developing a strategy.[326] This participant was too restricted by their framing and modelling of the problem and unable to adapt their approach to further fit the unfamiliar situation and the data they had available. This is seen when the participant, draws a model for the festival venue, frames the requirements for the problem, stating

> “*I like to use visualisation to see how big actually is the place and how many people we can accommodate in there… and we need space for the musical instruments etc. So from that we should be able to calculate the number of toilets we should have.*”

The problem with participant UHULLCH6’s framing of the problem was that it was not based on logical or scientific reasoning resulting in significant flaws and restrictions to their strategy. A further example of this was observed when the participant tried to calculate the mass of the Earth’s atmosphere based on the “*acceleration of the earth*,” stating “*the earth spins right so that should give us a speed for how fast it spins with all the planets around the sun*.” The participant clearly lacked an understanding about how to answer the problem, or even what the problem was asking them to do.

The results for the interdisciplinary science participants appeared very similar to the physical sciences participants and so they will be discussed in this section.

IIN+ Identifying the information needed is observed as a prominent approach in all interdisciplinary science participants' solutions (Table 18). Many participants asked for specific pieces of information before starting their solution, such as "*the average velocity at which a car travels*" and "*the number of revolutions of a car wheel*". In both of these examples, as with the other physical sciences participants, participants were trying to anchor their strategy and frame the problem. Participants also asked for pieces of information once they had started the solution. This was seen in participant ULEISCI5 who asked "*How many atoms are in a tyre.*" A further example was seen in participant ULEIISCI3 who stated "*Do you have the value for the number of molecules in the atmosphere?*" This emerged as the very last statement the participant made, identifying that the participant was still identifying the information needed , or rather asking for information to ensure there were no additional stages required to solve the problem.

Making approximations and estimations was common in all interdisciplinary science participants, with it being prominent in four out of seven participants (Table 18). This was seen in participant ULEIISCI6 who stated "*so lets say you've got an average of a 15 inch wheel. Seems pretty standard for wheel size as far as I know*". This example shows that there was no difference in the way approximations and estimations emerged when compared against physical sciences participants. A further example can be seen from participant ULEIISCI7 who stated "*the number of particles in the Earth's atmosphere, I believe is something like, approximately* 1.4×10^{44} *particles*". Interdisciplinary science participants used approximations and estimations throughout their solutions, normally following a phase of framing the problem and identifying the information needed, or following a stage of becoming confused with the problem. This was observed in participant ULEIISCI2 and ULEIISCI5 who both started making approximations once they had asked for information and framed the problem such as "*In uni blocks, there is much of a queue, so judging by personal experience there are going to be three toilets per thirty people*" (ULEIISCI2) and "*assume the size of 1m^3 size of particular waste, based on my own experiences.*" (ULEIISCI5) In both of these examples the participant had asked the interviewer for specific pieces of information which they were unable to provide. In an effort to avoid stalling their approach they made approximations and estimations to ensure they maintained momentum. Both of these participants showed that they were comfortable at making approximations and estimations.

Many participants from interdisciplinary sciences identified strategies for solving the problems which required the use of algorithms and calculations. This manifested through participants using equations such as "$mass = volume * density$" and "$PV = nRT$", as observed in the other physical sciences participants. One difference was the strategy employed by participant ULEIISCI3 who, upon identifying the information needed and framing the problem, seemed reluctant to solve the problem using algorithms and calculations, preferring instead to verbally reason their solution at times. The participant only made one calculation towards the end of their solution to problem 3. This reluctance to make calculations and use algorithms was also observed in participant UHULLCH6. Both these participants identified the information needed and framed the problem, but were not prepared to make calculations.

Interdisciplinary science participants either used lots of evaluation or very little. Only one participant (ULEIISC6) showed prominent evaluation and stated

> "*so 1 rotation of a wheel will get rid of one atom layer… and thinking about that it seems rather sensible because I imagine tyres made up of quite a lot of atoms so it would take a long time for the tyres to get worn down. So trying to think how often my dad changes his tyres.*"

In this example the participant showed clear reflection on both their strategy and solution and then proceeded to calculate an answer through a different method, triangulating their answers to see if they made sense. This participant showed signs of evaluation six times in their solutions. This is seen with the participant stating

> "*Well I have calculated the total number of minutes of toilet use that would used during the three day festival… I think I am over complicating this problem more than it needs to be, so maybe I could do it for just one person…*"

In this example the participant was clearly reflecting about their solution, and then once again proceeded to answer the problem a different way to check whether they solved it correctly.

Identifying and framing the problem is a common approach observed in interdisciplinary science participants with four out seven participants showing it as a prominent approach. Table 18 showed that interdisciplinary science participants always framed the problem towards the beginning of their solution, although it did emerge throughout the solutions. An example of identifying the problem and framing can be seen in participant ULEIISCI 2 who stated

> "*So I'm trying to think how fast a tyre loses mass. I'm guessing because it is an atom layer we would really notice it at all, so I'm guessing it is like every time a tyre experiences friction it would be lost*."

A further example can be seen in participant ULEIISCI 1 who stated

> "*hmm that is a very large festival. People are drinking so they are going to want to use toilet facilities quite regularly, 150,000 toilets is probably unfeasible although preferable but financially unfeasible*."

In both of these examples the participants are in the initial stages of developing a strategy and are trying to understand what the problem is asking, in particular participant ULEIISCI1 who is considering other impacts on the solution such as finances. Participant ULEIISCI4 was clearly framing the problem throughout their strategy. This is seen by the participant stating

> "*so there are* $6.022x10^{23}$ *molecules in a mole… and is it all four tyres for the wear. So that means we want to find out the distance travelled by the car in, I'm guessing that is kilometres*."

This example was just one phase of framing that emerges in the participant's solution, and they continued to frame the problem later in their solution (Table 18)

All but one interdisciplinary science participant was able to develop a strategy (Table 18). Some participants were able to develop multiple strategies in particular participant ULEIISCI5 who developed five strategies across the three problems. However, unlike the chemistry participants, this participant was developing multiple strategies to justify and check their solutions. There appears to be no link between developing multiple strategies and success through traffic light scores (Table 18), which is also observed in the physical science participants. Participants ULEIISCI4 and ULEIISCI5 had similar success at solving the problems with multiple strategies, however, participant ULEIISCI7 had the same success by only developing three strategies. Camacho and Good stated that knowledge of multiple methods to solve a problem is a characteristic of a successful problem solver.[360] However, our data shows that this is not necessarily the case.(Camacho and Good)

There were very few examples of participants becoming distracted by the lack of information. One example of this can be seen in participant ULEIISCI3 who stated

> "*hmm I don't have that data… So I would take sample tests to determine friction force needed to remove a layer… I would look at the average friction ratings for roads…*"

A further example can be seen in participant ULEIISCI4 who stated "*hmm, so that must be hours again then, oh so the number of uses of the toilet per hour then… so I still need to work out how many toilets are required*." Interestingly when participant ULEIISCI3 became distracted by the lack of information they were unable to think beyond that distraction, which is reflected in Table 18 with all red traffic light scores. However, participant ULEIISCI4 was able to overcome their distraction to a degree and achieve high traffic light scores.

All apart from one, interdisciplinary science participants were able to develop a logical and scientific approach to solving the problems. Participants usually adopted a systematic approach, grounding their reasoning in scientific principles. One participant, ULEIISCI3 was unable to develop a logical and scientific approach. This may be due to the participant struggling to develop a suitable strategy. The combination of not developing a strategy and lacking a scientific and logical approach is reflected in Table 27 with low traffic light scores. This participant scored all red solutions, in part because they were unable to develop a logical and scientific approach. What is unclear from this data is whether participants are unable to develop a logical and scientific approach because of a lack of developing a strategy or vice versa.

The individual radar chart profiles (as shown in Figure 28 and Figure 29) for the interdisciplinary sciences looked very similar to the physical sciences profiles (Figure 16 through Figure 23), with pronounced elongation in the IIN+ code (identifying information needed) and along the IPF+ code (Identifying and framing the problem). The percentage distributions are a little more spread out than in the physical sciences, with additional elongations along the A&E+ (making approximations and estimations) and positive ALG+ codes (using algorithms and making calculations). Most participants displayed IIN+ as the most common code, with the second highest split across more approaches including A&E+, ALG+, IPF+ and CCP- (becomes confused, lacks confidence with the problem). What is noticeably different between the interdisciplinary science and the physical sciences was a lower occurrence of the CCP- code. Although there is some prominence of this approach in interdisciplinary science participants it was much less frequent when compared against the physical sciences. This is reflected in the audio recordings of participants where the participants in interdisciplinary science gave the impression of having greater confidence when answering open-ended problems. One reason for this could be because these participants are taught using problem-based learning, and as such are more familiar with open-ended problems. However, some literature is dismissive of the constructivism approach, suggesting that minimal guidance and instructional approaches do not always prepare students for enquiry through problem solving.[349]

Minimal guidance approaches to learning are considered pedagogically equivalent in that learning is based on student-centred enquiry, where novice learners mimic the behaviours of professional researchers.[350] The philosophy was that "*large amounts of guidance may produce very good performance during practice, but too much guidance may impair later performance*."[351] Although the experience of interdisciplinary science participants taught through problem-based learning may be more confident and less confused with the problem solving experience, they are not noticeably more successful. Table 27 shows that interdisciplinary science participants are as successful at solving open-ended problems as physical science participants. Participants from interdisciplinary science used framing the problem and modelling in the same manner as participants in the physical sciences, using prior experiences, scientific knowledge and combining it with previous understanding to super imposing it onto a new problem. However Table 29 reflects that despite the problem based learning experience, interdisciplinary science participants were still novices at developing a strategy for solving open-ended problems.

Considering the definitions for novice problem solvers proposed by Walsh *et. al.*[326] and Camacho and Good[346], interdisciplinary science participants were still transitional rather than expert problem solvers. Walsh *et. al.* suggested that to become an expert at solving problems, participants must be reflective in their approach.[326] Becoming reflective whilst answering problems and evaluating both solution and strategy is identified as a characteristic that separates novice and expert problem solvers, a quality that was not emerging in interdisciplinary science participants.[158, 245]

Generally, there is commonality between the approaches used by participants in the physical sciences and interdisciplinary sciences. In addition to employing similar strategies, 34 participants (n=35) employed mainly positive approaches. (Tables 14, 15 and 18) Generally, participants focused on more positive approaches corresponding to those described by Walsh *et. al.* when investigating algorithmic problems in physics.[326] Whereas Walsh *et. al.* investigated quantitative problems with Newtonian mechanics, our study looked at open-ended problems. This may in part account the differences in profile with respect to successful and unsuccessful problem solvers in physical science undergraduate participants. Although participants displayed some of the characteristics identified by Walsh, they did not show every characteristic. Our study also did not identify five separate characteristics, instead preferring to traffic light success in solving problems and subcategorising approach profiles as mainly positive, mainly negative or mixed approaches. Overton *et. al.* reported the more positive approaches should correspond to more expert-like behaviour and overall a more scientific approach[316], although this paper uses the term ‘scientific approach’ as a description for an overall profile, whereas our study observed it as a separate emerging approach. The terminology ‘using a more scientific approach’ may not be appropriate in our study, because the term ‘scientific’ is encompassed within the Logical and Scientific Approach (LSA) code. Although the terminology is similar there is a difference in what they describe. It can be seen that participants in the physical sciences used predominantly positive codes, as shown in Table 14, Table 15 and Table 18.

However, they did not necessarily employ logical or scientific approach (LSA+) for every question. Participants did not have to use a logical and scientific approach to exhibit other positive approaches. The results for participants in the physical sciences and interdisciplinary science agree with those studies conducted by Walsh *et. al.*[326] and Overton *et. al.*[316] because they identify similar approaches used by physical science participants to solve open-ended problems as discussed earlier in the section. However, the measure of success in our study does not always reflect the approach profiles. This means that it may not be as simple as identifying the approaches used by individuals to train successful problem solvers. Open-ended problems may require more experience, rather than a systematic approach or flow chart system to follow.

The number of participants that had exhibited mixed approaches (using both positive and negative approaches) to solve open-ended problems was one (n=35) (UHULLCH6). Participants using a mixture of positively and negatively coded approaches partially agree with results found by Overton[316], Bennett[344] and Pappa and Tsaparlis,[345] who suggest that participants who use a wide range of approaches will focus on a strategy that includes algorithmic approaches. However, the results in our study would suggest that the use of algorithms is not unique to a mixed approach profiles and is also present in participants who adopted mainly positive approaches too. As stated previously a focus towards using an algorithmic approach is not surprising as algorithmic structure is a familiar concept to novice students, and resembles the problems that are most familiar to them.

No physical science or interdisciplinary science participants in this study used predominantly negative codes and therefore it is not possible to corroborate how such participants would deal with the lack of data and framing the problem. No participants in this study correspond to the definition of Walsh *et. al.*[326] and Overton *et. al.*[316] who suggest participants who showed predominantly negative approaches whilst solving problems become lost in the context of the problem and focus on seeking an algorithmic approach, a key component with their non-scientific/no clear approach categories.

As with the individual participant profiles the discipline profiles for the physical sciences and the interdisciplinary science partially agreed with studies of Overton *et. al.*[316] and Walsh *et. al.*[326] with the same limitations between the definitions for ALG codes and LSA codes as previously discussed. The overall profiles suggest that chemistry, physics and interdisciplinary science disciplines were still transitional, despite showing predominantly positive approaches. This is because Table 27 showed that there were varying degrees of success for each discipline despite similar profiles. The hierarchy was that chemistry disciplines performed worse at solving open-ended problems than interdisciplinary science who performed worse than physics.

Our study proposed that participants in the physical sciences and interdisciplinary sciences engage with open-ended problems using similar approaches, but differ between individuals based on mathematical ability, complexity of the problem framing process and evaluation. It is the inter-related connections between approaches rather than individual approaches that differentiates success at solving open-ended problems.

6.3 Approaches Exhibited by Sports Rehabilitation Undergraduate Participants

There are no reports in the literature of investigations of the approaches used by sports science or sports rehabilitation students when solving open-ended problems. In fact a large proportion of the literature researching undergraduate sports science and sports rehabilitation students relates to decision making skills and approaches during kinaesthetic activities (playing racquet sports, football etc.) or cognitive ability.[352-354] In contrast there is a wealth of literature for domains such as chemistry and physics. Therefore, to discuss our findings literature was drawn from chemistry, physics and generic problem solving domains.

Sports rehabilitation participants generally showed prominence in IIN+ (Table 16) and asked for a lot of information when solving the problems. Some participants asked for specific information once they had decided on a strategy. This was seen in participant UHULLSR2 who stated "*Do you know how much (salt) is lost per minute*." Here, the participant was identifying a specific piece of information they felt they needed to solve the problem. Another way in which sports rehabilitation participants showed IIN+ was to help identify and frame the problem (IPF+) in order to contextualise what is being asked, for example participant UHULLSR3 asked "*are we talking types of toilets do you need at a music festival.*" In this example the participant was querying the parameters of the problem by asking a specific question; this was coded as both IIN+ and IPF+. One participant failed to identify any information that they felt they would need to answer the problem.

Only half the participants in sports rehabilitation showed prominence with A&E+ (Table 16). Participant UHULLSR2 showed that they were not stalled by the interviewer being unable to provide the data they asked for. For example the participant made an estimation about the rate of salt lost per minute to be "*zero point three grams per minute*." A further example of participants making approximations and estimations is seen in participant UHULLSR5 who stated that a healthy athlete should be “*able to do a marathon in… say it took them three hours.*” And then further refines their estimation as “*three and a half [hours]*.” In this example it is clear that the participant was trying to progress their strategy further, despite not having the information they required through approximations and estimations. Overton *et. al.* state that participants who used predominantly negative approaches were incapable of making estimations or generating their own data.[316] Overton *et. al.* further state that participants that showed predominantly positive approaches were capable of making estimations and generate data.[316] Our research concurs with the findings of Overton *et. al.* where participant UHULLSR1, who showed predominantly negative approaches, appeared unable to make appropriate approximations and estimations. Furthermore, participants UHULLSR4-UHULLSR6 were identified as using predominantly positive approaches and were able to make estimations and approximations.

Very few sports rehabilitation students made calculations or used equations (ALG+), as shown in Table 16. Many of the participants preferred to reason their solution through guessing values, or verbally reasoning their answer (ALG-). Participant UHULLSR1 stated that “*probably about fifteen*,” toilets would be sufficient for a music festival, although when probed about their reasoning for their answer the participant stated “*past experience*.” A participant that did use calculations and equations was UHULLSR2 who states “*zero point three grams per minute, then if you times that by ninety for the full game*.” In this example the participant was calculating the amount of salt lost for the full game from an assumed lose rate per minute. In sports rehabilitation students the ALG+ identified that participants used only calculations and used no equations. Camacho and Good state that lack of mathematical skill can be a hindrance for problem-solving success, whereby misconceptions are serious enough prevent the participant dealing with abstract thought.[346]The required mathematical skill for sports rehabilitation students may be less complex than that suggested in the Camacho and Good study, however, other than participant UHULLSR6 sports rehabilitation participants did not show a strong prominence for ALG+, with participant UHULLSR5 identifying themselves as being "*really bad with maths*." Participant UHULLSR6 used more algorithmic approaches than the other participants, however showed no greater success than other participants (Table 16), although incidentally achieved greater success on a problem where they used no ALG+ approaches.

Evaluation (EVA) in sports rehabilitation participants emerged infrequently. Only two participants showed signs of evaluation of their solution or strategy. Participant UHULLSR4 states

> "*Well it's definitely more than that. Four percent is a small thing though… but it's not that small though. Personally I think I did the adding up wrong. But that's only because I cannot remember how to do maths at all*."

In this example the participant showed signs of reflection on their strategy but failed to further their evaluation. This is because they thought the answer was incorrect because of a flaw in their mathematical knowledge. No evaluation occured during their solution to reflect whether this was the correct strategy. A further example of evaluation was identified in participant UHULLSR6 whilst solving problem 1. The participant used a plug and chug strategy which meant they evaluated their solution following a calculation, deciding whether the value obtained was appropriate. The evaluation in sports rehabilitation participants appears less ‘meaningful’ than physical science participants, and appears more of a reflection than evaluation. This is because the reflection is not actioned upon within the solution.

Sports rehabilitation participants attempted to contextualise the problem by identifying and framing it (IPF+). About half the participants showed prominence (Table 16) for this approach, and all but one participant showed signs of identifying and framing the problem. Identifying and framing the problem emerged in participant UHULLSR3, as previously discussed, through asking the interviewer for a specific piece of information. The information was then used to contextualise the problem and to develop a particular strategy. A further example by the same participant is seen in problem 3 where the participant states “*Well I’ve got friends that run them and they normally do them in three hours so… depends whether we’re talking about your average joe or a professional athlete*.” In this example the participant was trying to identify a way to develop a strategy by identifying what they already understood and how it could fit into the context of the problem. A final example of identifying and framing the problem used by sports rehabilitation participants can be seen in participant UHULLSR5. The participant states they “*need breaths per minute… I’m trying to remember what a normal person does a rest*,” (breathing during a marathon). In this example the participant was framing a particular part of the problem, identifying also how they wanted their strategy to proceed. Overton *et. al.* state that participants that show mainly negative approaches were unable to identify what the problem was asking.[316] In their study they reference a participant who stated “*one follicle per second… I can’t answer that, I don’t know where to start. I don’t know how long a protein takes… I don’t even understand it*.” In the example presented by Overton *et. al.* the participant was clearly struggling to contextualise the problem. However under the coding system outlined in this thesis, the quote presented would also reflect the participant becoming confused with the problem (CCP-). Overton *et. al.* further discussed that participants that showed predominantly positive codes are able to ‘clarify’ the problem objectives more easily[316] and further stated that a participant who shows a mixture of approaches would show a mixture of characteristics of both positive and negative approaches.[316] The research conducted in this thesis support these findings. Participant UHULLSR1 showed predominantly negative approaches and struggled or failed to identify the problem. Participants UHULLSR2 and UHULLSR3 show a mixture of approaches, and as such showed a mixture of success at identifying and framing the problem. Participants UHULLSR4-UHULLSR6 showed predominantly positive approaches, and were able to successfully identify the problem.

For the most part participants in sports rehabilitation were able to develop appropriate strategies to solve open-ended problems (DAS+), with one participant showing prominence during their solutions for developing a strategy (Table 16). In sports rehabilitation the development of a strategy emerged as a series of events reported holistically, rather than discrete events. Participant UHULLSR4 for problem 1 clearly identified that they want to identify the appropriate number of toilets over a given area based on how many people are attending the music festival. The same participant in problem 2 identified that they wanted to calculate the amount of salt lost through sweat by calculating the rate of sweat and the concentration of salt in sweat. Sports rehabilitation participants develop a single strategy, unlike some members in the physical sciences, even when the strategy is flawed. Where participants are not developing strategies, the participants made guesses. Overton *et. al.* indicated participants who demonstrated predominantly positive approaches are able to develop strategies quickly when answering a problem.[316]. In our study the sports rehabilitation students who had more positive approaches were able to develop a clear strategy to answer the problem, although most participants expressed developing a strategy in one discrete statement, rather a progressive series of statements.

Participants from sports rehabilitation did not easily become distracted by the lack of information (NDIS-) (Table 16). Participant UHULLSR4 became distracted by the lack of information, when solving problem 2 by not knowing the fitness level of the football player stating

> "*cause it would depend if they were large wouldn't it cause then they would lose a lot more, where as if they are very fit. I've never thought about how much in the way of litres you would lose*."

In this example, the problem did not state the fitness level of the football player, and so the participant became distracted by the lack of this information and unsure how to proceed with the problem. The study by Overton *et. al.* identified participants could become distracted by their previous knowledge, but not specifically by the lack of information. [316] Becoming distracted by previous knowledge was an approach that our study did not see emerging from the data, and distraction was specifically associated with the lack of information as demonstrated through the above quote.

No participant from sports rehabilitation were able to develop a logical and scientific approach (LSA-) to their solution (Table 16). This was seen by participants guessing and not thinking systematically. Furthermore, participants in sports rehabilitation stuck rigidly to a single strategy even when the strategy was flawed. This may be in part due to the lack of identifying and framing the problem, and the lack of evaluation.

The CC codes for the sports rehabilitation participants showed a mixture of emergences. Participants UHULLSR2 and UHULLSR3 displayed a mixture of positive and negative approaches which followed through to the confidence/confusion codes. These two participants showed a mixture of being confident and lacking confidence or becoming confused depending on the problem they were solving. For example UHULLSR2 showed only one incident of lacking confidence in their ability which emerged with the comment "*How do I convert that into grams?*" Although the words by themselves may look like an IIN+ code the question was not directed at the researcher and the tone of their voice was questioning their ability. Participant UHULLSR3 also showed signs of lacking confidence in their ability, both of which occurred in question 3. The participant states "*We've done V O two tests but it sounds like something I should know*." Again in this example the participant was questioning their ability to recall something with an irritated tone in their voice. In both of these examples the participants were expressing their lack of confidence in their ability over something they believed should be simple recall of a fact.

The individual profiles for sports rehabilitation looked very different from each other (Figure 24), when compared against the discipline overall. However, using Table 16, it was seen that three different problem solver profiles were emerging. Participant UHULLSR1 showed predominantly negative codes with no prominent code emerging. The only positive code presented by this participant was the NDIS+ (not distracted by additional details or context). The profile exhibited by participant UHULLSR1 resembled the approaches seen by

Overton *et. al.*, for which they described individuals using predominantly negative approaches as 'novices'.[316] This was a theme reiterated by Bodner and Domain, and later by Cartrette and Bodner, who described problem-solvers who used an unstructured approach to solving problems as novices.[355, 356] One theory for the unstructured approach was the individual's inability to organise memories and categorise cues within a problem in a specific way, a characteristic seen in chess players as they develop a strategy to win.[357] However our research with chemistry and physics participants would suggest that it is not only the organisation of memory that is important to be a successful problem solver, but also the ability to identify and frame the problem. Participant UHULLSR1 not only had no method to answer the open-ended problems, they had no experience or ability to anchor the development of their strategy. This was shown in particular in question 1 for this participant as discussed earlier. What was further observed with this participant was that they didn't ask for specific pieces of information, instead guessing throughout their problem solving, showing almost no framing of the problem and taking no opportunities to ask for information. However, one example of framing the problem emerged in question 3. The participant stated they were "*trying to think how big the lungs*" were. What was clear from this participant was that they were incapable of developing a suitable strategy for these three open-ended problems.

Participants UHULLSR2 and UHULLSR3 displayed mixed approaches with fairly even coverage between positive and negative codes, and showed evidence that they were trying to probe the problem. These participants showed less novice like approaches than participant UHULLSR1, however, cannot be considered to have transitioned from being novice problem solvers. That is because despite showing mixed approaches, categorised by Overton *et. al.* as transitional[316], they did not show sufficiently different characteristics under the Walsh *et. al.* and Camacho and Good definitions.[326, 346] Under the Camacho and Good definitions, novice problem solvers were unable to perceive a strategy for the problem, develop content knowledge and represent the problem in a meaningful way.[346] This was shown in participants UHULLSR2 and UHULLSR3 where despite using a mixture of positive and negative approaches, they still did not sufficiently identify the information needed (IIN+) and focused mainly on framing the problem (IPF+). Therefore, these participants did not perceive a suitable strategy to answer the problems. Participant UHULLSR2 asked for specific details as part of identifying and framing the problem. This emerged in question 2 where the participant asked "*do you know how much is lost per minute?*" Although these two participants asked for specific information, the interviewer was unable to provide them with it. This resulted in the participants seeking their own values through making approximations and estimations. For example UHULLSR2 when the interviewer was unable to provide them with information stated "*ok, lets say they lose zero point three grams per minute*." What was interesting was that participant UHULLSR3 only asked for specific information in question 1. The participant asked "*are we talking types of toilets or just the general number in total for an entire site,*" the interviewer was unable to provide them with those details. The participant then no longer asked for further details from the interviewer, instead preferring to estimate the values themselves. This was seen when the participant stated "*well my friend does it in about three hours to run a marathon*." Both participants UHULLSR2 and UHULLSR3 used identifying the information needed as an additional stage of identifying and framing the problem. Under the Walsh *et. al.* definitions for problem solvers participants UHULLSR2 and UHULLSR3 were still not developing a clear approach because they were not evaluating their solutions or answers.[326]

Participants UHULLSR4 and UHULLSR5 displayed predominantly positive codes, which under the Overton *et. al.* definition would mean that these participants were expert problem solvers.[316] The participants displayed predominantly positive codes and showed prominence in IIN+ (identifying information needed) code asking questions such as "*what type of athlete are they?*" and "*how much does a person sweat normally?*" This additional framing stage by asking for specific information (IIN+) showed that there was an emerging novice. Despite using predominantly positive approaches these participants still showed low success at solving the problems (Table 27). This again suggests that it may not be sufficient to utilise predominantly positive approaches to be successful at solving open-ended problems, and that developing opportunities for experiencing open-ended problems may be required. Walsh *et. al.* stated that novice (no clear approach) participants analyse the situation based on given variables.[326] Both these sports rehabilitation participants were actively seeking further information, not content with the information provided in the question, and as such sought additional variables to anchor their approach against. Participants UHULLSR4 and UHULLSR5 displayed some but not all of the characteristics of memory-based approaches proposed by Walsh *et. al.* suggesting they were on the cusp of becoming transitional by trying to 'fit the information to previous examples.'[326] A memory based approach held the characteristics of analysing the situation based on previous examples, proceeds trying to fit the given variables to those examples, refer to concepts as variables and conduct no evaluation. What is very different for participants UHULLSR4 and UHULLSR5 from the other sports rehabilitation participants is that they were able to develop a coherent, but still flawed, strategy. Both participants spent a short time identifying and framing the problem, asking specific questions which they then used to further the development of their strategy, an approach seen in many chemistry and physics participants. However as with the other participants, no evaluation of their solution or strategy was vocalised by either participant. Walsh *et. al.* believe that in order to use a scientific approach then the participants must use evaluation. Therefore despite meeting the requirements for expert problem solver under the Overton *et. al.* paradigm the lack of evaluation, and the ability to adapt their approach to be more logical and scientific meant that they could at best be described as novice/transitional. This is reflected in Table 27 where participants achieved low traffic light scores despite the more positive approaches used.

Participant UHULLSR6 showed emerging approaches IPF+, ALG+ and A&E+ in a profile that differed to the other three types of profiles for sports participants. This student chose to develop a more numerical response to the problem instead of guessing at variables or the answer (as seen in participants UHULLSR1, UHULLSR2 and UHULLSR3). This behaviour displayed some of the characteristics associated with the Walsh *et. al.* 'unstructured plug and chug' approach.[326] This was observed by the participant stating that "*1 toilet for every 20 guests*" at the beginning of their strategy however this value was revised to "*1 toilet in every 50 guests*," because 1 in 20 seemed a too high number of toilets. At this point UHULLSR6 was continually framing the problem and revising and refining their approach. This did demonstrate some evaluation, however the reasoning was grounded in nothing other than their gut feeling and lacked meaningful scientific grounding and, as such, the evaluation was of poor quality.

What is interesting was that sports rehabilitation participants who exhibited mainly positive codes (UHULLSR4-UHULLSR6) were the participants that showed the most confusion with the problem (CCP-). What isn't clear is why this is the case. An example of CCP- shown by participant UHULLSR4 who stated "*No what am I doing? What would that be? Mmm three hundered toilets*." In this example the participant was trying to gauge whether the value they had was appropriate as they struggled to contextualise their answer. Based on the words alone it may be considered evaluation, however, the tone of the voice and the actions they take made it clear the participant was confused by the problem. A further example from this participant was "*you don't lose litres through sweat though do you? You can't do can you?*" In this example the participant is questioning whether they have appropriately framed the problem, in essence reflecting on their strategy, again the tone of voice identified more with confusion as the participant did not act upon their reflection further. What is more clearly understood is that most of the confusion in these participants occurred whilst participants were evaluating their strategy or solution or questioning how their response fitted into what they understood. However, the degree of confusion and confidence is not reflected in the success of their problem solving, as there is little difference in success between sports rehabilitation participants, and as such they should be considered novices.

The overall discipline profile in Figure 25 showed that there was a mix of approaches with slight prominence in the IIN+ code. This differs from those profiles in the physical sciences and interdisciplinary sciences which showed prominence predominantly for positive codes. The code CCP- also showed prominence. This emerged in participants' responses with phrases such as "*well that's a really weird question. Well no, it's not a weird question, it's just a really* *hard question*." Furthermore, the code CCA- showed that participants lacked confidence in their ability at some stage. This could be seen with the following statement of "*why didn't I stay studying maths at school*." This comment also gave an indication that participants might not have used many calculations or algorithms because they didn't know how to. This refers to content knowledge and strategy knowledge, reported as being desirable for expert problem solvers,[346] but lacking in sports rehabilitation.

Emerging from the sports rehabilitation participants was a continuum of novice behaviour at solving open-ended problems wherein participants used approaches associated in previous literature that should produce expert problem solvers. However, these participants who showed more 'expert like' behaviour were no more successful at solving problems than participants that showed 'novice like' behaviour. This may be because open-ended problems require more diverse approaches than algorithmic problems to achieve success, or rather the quality of the approach impacts on success. Smith and Good investigated the performance of participants answering 'moderately-complex genetic problems'.[358] When they analysed their data they identified 32 approaches which could differentiate between successful and unsuccessful problem solvers. In this study they identified a sliding scale of expertise starting with novice and transitioning towards more expert like behaviour.[358] Camacho and Good[346], and Overton *et. al.*[316] also identified the split between novice, transitional and expert problem solvers, although Camacho and Good observed it as a continuum rather than more discrete categories as in Overton *et. al*. In our study, discrete categories of expertise for individual problem solvers may be inappropriate when a large difference is observed with in a discipline and a continuum from novice to expert behaviour maybe more appropriate when considering the approaches used, whereby individuals use approaches associated with expert behaviour. However, the traffic light data must also be taken into consideration. This is reflected in Table 27 which documents participant success at solving open-ended problems. In all six cases the participants in sports rehabilitation scored the same, showing low success at solving open-ended problems, despite exhibiting very different profiles. This may have identified that despite having similar success at solving problems, the quality of what the participants are doing is more important than cataloguing that they use specific characteristic. This means that it may not be sufficient to tell students how to solve problems through discrete steps but rather develop their experiences in answering open-ended problems. This may enable them to transition from novice success, as seen in the sports rehabilitation participants, towards greater expert success at solving open-ended problems.

6.4 Approaches Exhibited by Psychology Undergraduate Participants

Once again there is no specific research reported on open-ended problem solving in psychology undergraduate students, and studies found investigated cognitive load theory and the relationship of learning with psychology as a discipline rather than specifically identifying participants as psychology undergraduate students. This means that psychology students will be compared against literature associated with chemistry, physics and generic problem solving in undergraduate students.

Psychology undergraduate participants showed differences in how much they identified the information required for their solution (Table 17). Four participants showed prominence of IIN+ (just under half of participants).

However, two participants showed 0% distribution for the IIN+ code. An example of psychology participants showing IIN+ code can be seen in participant UHULLPS3 who stated the number of toilets would "*depend on the size of the venue*," and "*the number of bands*." What is interesting about this participant is that, despite being told they may ask for specific information, they only identify the information needed instead of asking the interviewer for the details. IIN+ emerged in participant UHULLPS6 with "*how many people do you have in a night club?*" and "*is that as in like say the night before being an episode?*" In both of these examples the participant is using identifying the information needed as an additional framing process for the problem.

Psychology participants frequently made approximations and estimations (A&E+), with seven participants showing prominence in this approach. Approximations and estimations appear to have emerged as an alternative to asking the interviewer for specific information. This is observed in Table 17 which showed that participants who didn't ask the interviewer for information (IIN+) still made approximations and estimations (A&E+). Participant UHULLPS4 was an example of this and stated, "*well there's probably about 50 people to, fifty people to every toilet*" thereby making an estimation to which they anchored the rest of their solution. Other participants used approximations and estimations in combination with identifying the information needed. Table 17 shows that UHULLPS7 used a combination of estimations and identifying the information. An example of approximations used by this participant is "*so six units [of alcohol] per person,*" and "*200 people in a nightclub*" showing that they were able to make appropriate approximations and estimations when required. Overton *et. al.* suggested that participants who show a mixture of positive and negative approaches are transitional, and show the characteristics that would allow them to perform both as novices and experts depending on the situation.[316] Camacho and Good state that to be successful at solving problems participants must be able to "*make proper assumptions and approximations when needed.*"[346] In our study participants showed signs of both able and unable to make appropriate approximations and estimations, this would suggest that some participants may show this approach and still not be considered expert problem solvers. However, participants who were able to make appropriate approximations and estimations may be considered to show expert behaviour, but when considering the traffic light data from Table 27 it is clear that being able to make appropriate approximations is not sufficient to steer an individual towards a successful solution. This is comparable with the other disciplines in our study.

No psychology participants showed prominence at using calculations and equations and, as Table 17 shows, only one participant made a calculation during their solution. Participant UHULLPS1 made and wrote the calculation '15 x 3' to calculate the number of toilets required at the music festival. Other participants attempts at making calculations, however, never followed through with their plans and they instead preferred to make estimations. The lack of using calculations and algorithms was something that hadn't been seen in previous groups of participant. The physical science and sports rehabilitation participants for the most part used calculations to develop their solutions, however the psychologists preferred to reason their solutions verbally rather than numerically. Camacho and Good state that to be a successful problem solver participants must "*show proper knowledge and use of these and other mathematical skills.*"[346] Although the questions for psychology participants could be answered using both verbal and mathematical reasoning, it is clear that some psychology participants lacked a willingness to use numerical reasoning. This was seen in participant UHULLPS6 who stated "*so I need to think figures now don't I. Oooh, that's awful.*" Psychology participants also identified they are uncomfortable with mathematical components of the problem with participant UHULLPS3 stating "*This is maths, very early in a morning isn't it… Oh I can't work it out, why can't I work it out.*" This example further exemplified psychology participants' lack of willingness to engage with the problem numerically, supporting the suggestion by Camacho and Good that knowledge of mathematical skill aids problem solving ability.

Table 17 showed only two examples of evaluation were observed in psychology participants. Participant UHULLPS2 stated that "*actually it might be more than that. Hmm. Ok. I'm thinking there is maybe a hundred people there*." In this example the participant was evaluating whether a hundred people would be appropriate for a night club attendance. Although that value may be small, the participant took action after evaluating the approximated value. Another example emerged in participant UHULLPS3 who stated

> "*there can't be half a million children with ADHD… that can't be right can it. A hundred divide by… they wont all get a statement. So… cause some might not be severe enough and some might go un-noticed*."

In this example the participant was clearly evaluating their final solution after a stage of reasoning statements. This participant differed from the previous example and participants in sports rehabilitation because they refined their solution further following the evaluation stage.

As observed in the sports rehabilitation participants, psychology participants preferred to frame the problem using prior experiences rather than constructing a theoretical model. One example is seen in participant UHULLPS3 for question 2 who states "*well, one bottle, well talking of experience of me and my friends, one bottle of wine is usually enough to impair memory.*" In this example it can be clearly seen that the participant was contextualising and framing the problem based on a personal experience . A further example of this framing process was observed in participant UHULLPS6 who for question 3 stated "*I would probably work it out by how many people do I know with ADHD, but they're not children, they're adults and I only know three.*" Once again in this example the participant was framing the problem based on their experience.

The ability of participants from psychology to develop a strategy was mixed, as shown in Table 17. Some participants, such as UHULLPS1, were able to develop clearly defined strategies with clear objectives. An example for problem 2 used a strategy which involved calculating the total number of alcohol units based on the number of units of alcohol per person. Although there are examples of psychology participants developing clear strategies, there are also psychology participants who couldn't, such as participant UHULLPS6 who struggled to engage with any of the problems, and was unable to provide an solution to two of them.

Participants in psychology showed large variation in becoming distracted by the lack of information (NDIS-), and Table 17 showed that most participants became distracted. An example of this is participant UHULLPS6 who stated, "*How many units of alcohol… well you can't really answer that can you? Cause… it depends on the metabolic rate of the person and their fitness levels… you can't really answer that question. It's too ambiguous*."

In this example the participant was clearly distracted by the lack of details and information provided in the question. The participant became so distracted that they are unable to develop a strategy to answer the problem (DAS-). However, becoming distracted by the lack of information did not always result in lack of a strategy. Participant UHULLPS8 became distracted in problem 2 stating that impairment depended on "*the drink too, cause the question doesn't specify a drink does it… it doesn't specify ow much is suppose to impair memory*." In this example the participant was questioning the parameters of the problem, although was unable initially to think past the lack of this information.

No participants from psychology showed prominence for using a logical and scientific approach (LSA+), and Table 17 shows that only one participant UHULLPS8 showed a logical and scientific approach during problem 3. In this example the participant isolated the number of children with ADHD in the UK by determining what percentage of the population in the UK are children. Although the participant used no calculations, and used a flawed strategy and assumptions, they demonstrated a systematic approach.

For the CC codes for the psychology participants, many of the participants showed a mixture of being confident/ not becoming confused (CC+), becoming confused with the problem (CCP-) and lacking confidence with their ability (CCA-). For example, UHULLPS8 showed a fairly even coverage between all three confidence codes. However, some participants showed a emergence of specific confidence behaviours. An example of this is participant UHULLPS6 who became confused with the problem repeatedly stating they "*didn't know*" what they were doing, and finally stating "*these are very ambiguous questions, very interesting questions*." This final comment may suggest that the participant's main issues were with the type of problem and they were unsure what to do. Statements of 'I don't know,' were common throughout all psychology participants who showed signs of lacking confidence with the problem. Some participants showed a lack of confidence in their ability. This is repeatedly seen in participant UHULLPS3 who stated "I am rubbish at these [problems]… will I mess up your data?" and "I can't work it out… why can't I work it out." This lack of confidence in their own ability was less common in psychology participants than confusion with the problem. This may be because participants were struggling with the parameters of the problem and therefore had less time to reflect on their own ability.

The individual profiles for students studying psychology looked very different when compared against each other, with fairly even coverage of both positive and negative codes amongst a majority of participants. Overton *et*. *al*. would identify these participants as being transitional because they exhibited a mixture of positive and negative approaches.[316] However, this definition is not giving the true indication of the ability of individual participants in our study, and the individuals are certainly not transitional because the traffic light data in Table 27 showed that the participants all scored poorly. In fact, the approaches emerging from psychology participants were very similar to some of the sports rehabilitation students, where the students are still novices despite showing some characteristics of expert problem solvers. When these participants were compared to the definitions of Walsh *et. al.*,[326] the participants showed 'no clear approach', rarely exploring variables beyond those presented in the question, and where participants did explore variables further they become distracted by the lack of information. This was interesting because NDIS- code had not been observed in participants from the physical sciences. In generalised terms the participants fitted well under the Camacho and Good definitions for novice participants, as they were unable to perceive a suitable strategy.[346] This was supported by the traffic light data in Table 27 which would identify all participants as scoring low success at solving open-ended problems. With this low score from the traffic light data, it was difficult to support any other definition other than novice problem solvers.

Table 17 showed that there are two exceptions to the definitions outlined by Walsh *et. al.* and Camacho and Good. Participant UHULLPS3 displayed more positive approaches than other psychology participants, and engaged with a mixture of memory based approaches and trying to develop content knowledge. The participant showed prominence in the IIN+ (identifying information needed), A&E+ (making approximations and estimations) and IPF+ (identifying the problem and framing). It could be proposed that participant UHULLPS3 was showing less novice-like approaches than the other psychology participants. An example of INN+ used by participant UHULLPS3 was "*[do you know] the number of people attending [the festival],*" and "*what's the population [of the UK]*." When compared against participants within their own discipline it clearly showed acquisition of additional variables which were not seen in other psychology participants. Overton *et. al.* would suggest that this participant was showing more expert-like behaviour than the other psychology participants, this is because the participant showed prominence of only positive approaches.[316] However, it is difficult to state that this participant was an expert problem solver because they were unable to develop a logical and scientific approach, and there are too few examples of evaluation, all approaches Overton *et. al.* identified as being important to be an expert problem solver. The difference in their expertise over the other participants is reflected in their greater success where they scored all amber solutions (Table 27), higher than the other participants in the psychology cohort. This would suggest that the participant is more transitional rather than novice or expert when solving open-ended problems.

Participant UHULLPS6 also split their focus between three different approaches, one positive and two negative. These approaches were IIN+, CCP- (lacking confidence and becoming confused with the problem) and NDIS- (becoming distracted by details or lack of information), with little to no distribution amongst the other codes. The incidents where participant UHULLPS6 used NDIS- are "*I would think for a safety and a welfare issue we'd have gone on a percentage issue*," and "*well you can't really answer that can you? [because] it depends on the metabolic rate of the person.*" This participant showed a definite reluctance to proceed with answering the problem because of the lack of information and became distracted, as such they could be considered at the lower end of the problem solving novice spectrum.[316, 346]

A further characteristic that was present in a majority of participants was the desire to relate the unknown experience to a former, similar experience , a behaviour which will be referred to as 'templating'. What was noticeable about the psychology participants with regards to templating was their inability to adapt their templates to the situation. One example of this was UHULLPS6 who were considering how many children in the UK have ADHD. The template they used was their own friendship group, and stated "*I only know three*" people in their social group that have ADHD. However, what they fail to do was adapt their template and evaluate whether their social group is a true reflection of the general population. This example was similarly mirrored throughout the solutions for psychology undergraduate participants, showing either a reluctance to step away from something they already know, or an inability to adapt to a different situation.

As a discipline Table 17 showed that participants in psychology employed a mixture of positive and negative approaches, but remain novice problem solvers. This is very different from their counterparts in the physical sciences and interdisciplinary sciences, who show greater focus on their approaches to what Walsh *et. al.* label as unstructured/structured plug and chug techniques.[326] Both sports rehabilitation and psychology could both be classified as mixed, exhibiting behaviours that would place them as novices. The difference is that the discipline profile for sports rehabilitation shows only seven codes as being prominent, but the psychology profile shows that ten codes are prominent. The difference in the number of prominent codes is reflected in the radar diagrams which showed a more rounded shape for psychology when compared against all other disciplines. The radar diagrams in Figure 27 reflected the approaches reported in the Overton and Potter study.[316]

6.5 Approaches Exhibited by Pharmacy Undergraduate Participants

There are no reports in the literature that investigate the problem solving ability and approaches of undergraduate students studying pharmacy so this section will draw on literature already established in chemistry, physics and the general problem solving domains

Pharmacy participants showed a range of prominence of IIN+, suggesting that some participants had difficulty when identify data required to answer open-ended problems. The participants who did show high levels of IIN+ asked for specific data such as "*do you know how much sweat is lost per minute?*" and "*what is the breathing rate of an athlete?*" and a majority of the time the IIN+ was being used as an additional framing process to ascertain how to answer the question. As discussed previously, IIN+ was found emerging as both a framing process and a continuation of data acquisition once a participant had started their strategy. However in pharmacy participants IIN+ was predominantly used during the framing stages when participants were using IPF+ too. Generally, once participants had a piece of information they thought they could use, more specific data was asked for such as "*Do you know the capacity of the lungs?*" and "*Do you know how much* CO_2 *is in the lungs?*" The use of this approach is similar to the way it was used by physical science participants. Literature such as Walsh *et. al.*[326] and Camacho and Good[346], suggested that participants must be able to identify the information needed to be successful at solving problems. Camacho and Good stated that participants who are successful at solving problems are able to "u*se other information not given in the problems,*" whereas unsuccessful problem solvers will "*repeat the same information given in the problem*."[346] When the traffic lighted data is taken into account (Table 19), the approach data partially agreed with Camacho and Good in that no participant who identified the information needed to solve a problem was successful at solving the problems. However, the ability to identify the required information needed was not a predetermination for success. The study by Walsh *et. al.* states that participants who were unable to identify the additional information needed "*proceed by trying to "fit" the given variables to* *examples*" and that these participants were using a memory-based approach.[326] They further suggest that participants who "*proceed by trying to use the variables in a random way,*" had no clear approach to solving problems. Both these types of participants are seen to a limited degree in the pharmacy participants whereby they try to identify data directly identifiable from the problem, rather than thinking about parameters and concepts beyond those given in the problem. Participants from this cohort were limited in identifying the information needed through their inability to frame the problem.

Pharmacy participants made approximations and estimations , although as Table 19 shows, it was infrequently observed. Where participants did use approximations and estimations it usually followed them asking for information which the interviewer was unable to provide. This was observed in participant UMONPHAR12 who stated "*lungs… 3 litres in total, because five percent of three litres you can expect to find how much has exhaled.*" This example demonstrates the ability of the participant to think about how they were approaching the problem. The participant wanted to ensure it was a realistic value, but also a number that would make other calculations easier. Some participants across all the disciplines made unrealistic estimations and approximations to make the maths fit; this meant they struggled later to evaluate, because their results were not what they would have realistically expected. Participant UMONPHAR12 appeared to understand this and throughout the problem solving they estimated realistic, but easy to use values to ensure their strategy did not stall. A further example of this was observed in participant UMONPHAR1 who stated "*hmm, I'm going to say average time spent [on the toilet], I'm going to say five minutes.*" In this example the participant was ensuring they could maintain their chosen strategy, despite the interviewer being unable to provide the information. Overton *et. al.* suggested that participants that showed mainly positive approaches should be the individuals who were able to make estimations and Table 19 shows that held true for most pharmacy participants.[316] However, there was a slight difference with participant UMONPHAR2 who showed no signs of making approximations and estimations in any of the problems, despite using mainly positive approaches. As with the psychology participants, many of the pharmacy participants in our study were transitional. Under the Overton *et. al.* paradigm, participants who showed a mixture of positive and negative approaches were considered transitional and, therefore, may have the capacity for making approximations and estimations.[316] This is clear in Table 19 where some pharmacy participants showed a mixture of positive and negative approaches and yet still made approximations and estimations. Some participants under the transitional definition were unable to make approximations still, which was again supported by the Overton *et. al.* study.[316] However, as Table 27 shows, even though participants were showing characteristics indicative of being transitional and expert problem solvers, their success rating at answering open-ended problems was predominantly unsuccessful. Participants who scored low for success can only ever be referred to as novice problem solvers, despite showing characteristics beyond those associated with novice problem solvers.

Pharmacy participants used algorithms and equations to varying degrees and with varying success. Participant UMONPHAR10 stated "*c is equal to forty milimols, which is forty times ten to the negative 3 moles. And V is equal to, what did I say, five hundred mils. I would say that is the volume*". The participant then proceeded to use the equation n=cV to calculate the number of moles of sodium chloride present in sweat. The participant clearly was making purposeful calculations, rather than fruitlessly searching for a calculation or equation to use in their strategy, and proceeded to use an additional equation to transform the number of moles of sodium chloride in sweat into a mass using the equation m=n/Mr. Using equations and making calculations were not prominent in participant UMONPHAR12 but they stated "*the mass of sodium chloride lost is zero point zero six moles times by, what is Na?.. twenty three, and chlorine is 35.5*." and wrote $m(NaCl)_{lost}$ = 0.06mols x (23.0 + 35.5). From this example it was clear that the participant understood not just how to make the calculation, but also why they were completing the calculation. Prior to this the participant demonstrated further understanding by stating "*forty over a thousand, sorry I just need to get this through my head because I am not good at chemistry… so forty over a thousand, moles. Is… zero point zero four moles.*" In this example the participant exclaims they were not confident with their chemistry knowledge. The participant is checking what 40 milimols actually meant, and checked this value through a calculation. It was unclear why some participants did not make calculations or use equations in their strategy, although it may be due to them struggling to link the problems with mathematical tools. In other words, they knew what they wanted to do, they were just unable to make the correct calculations or identify the correct equations they needed. Participant UMONPHAR4 showed predominantly negative approaches, with moderate attempts to identifying and frame the problem. This would suggest that the participant was able to link the different variables to the problem and understood what was required but lacked the mathematical tools required for the problem. However, the participant never stated or acknowledged their mathematical limitations which made it difficult to identify why they never used equations or calculations in their strategy.

Table 19 showed that undergraduate participants in pharmacy used evaluation infrequently. Evaluation manifested in pharmacy participants predominantly as evaluation of their strategy, with few examples of reflection upon their final solution. Participant UMONPHAR12 showed evaluation in all problems and stated that "*he is going to sweating at an increasing rate, no shall I complicate things or just assume that it is constant. Shall I make it more complicated for myself… Ok We will assume that it is constant*". This clearly showed that the participant was thinking not only about what strategy they had used, but also how to proceed to correct the problem. This participant was still in the process of developing a model to solve the problem, but was reflecting on how complex a model to develop. The participant, however, was more worried about their ability to solve a more complex problem rather than the nature of their model. This showed that the participant is acknowledging the limitations in their ability and was thinking about the problem as a whole rather than just the discrete stages. This amount of evaluation was uncommon in the pharmacy participants. However, participant UMONPHAR5 reflected on the development of their model but they repeatedly engaged in flawed evaluation, despite reflecting upon their solution. This is seen in in

> "*I need something that I know is ten kilograms, as that would be all C O two that someone has exhaled…but what if it's like in the hundreds of kilograms. No I think that would be too much, but I don't know… No I'm going to go with… C O two is not that heavy. I'm going to go with like ten kilograms, or nine, or eight.*"

This example showed the confusion the participant was going through whilst evaluating their solution. Having evaluated their solution, they felt that the solution was too low, and were concerned the value would be much higher.

Throughout the example the participant was in conflict about their answer because they were unable to scientifically reason the value they had, later stating it was "*an outright guess*." Although the participant guessed an answer, they attempted to reason through how appropriate the guess was, and therefore were able to reflect whether it made sense. Unfortunately for the participant the evaluation failed to identify the flaws in their solution, resulting in a failed answer. Overton *et. al.*[316], Walsh *et. al.*[326] and Camacho and Good[346] all identified that evaluation was a key part of becoming successful at solving problems. Table 19 showed that participants from pharmacy showed some evaluation, however the meaningfulness of that evaluation and the actions taken are less clear. Table 37 identified the timeline of when each approach emerged and showed further where participants were evaluating (EVA+) they were evaluating their strategy not the final solution. The lack of evaluation of their end solution was interesting, and may explain the low traffic light scores in Table 27.

Identifying and framing the problem (IPF+) emerged in all participants through statements like

> "*first you need to know what type of music festival it is" and "I'm going to assume that this guy is going to be running around a lot and drinking water to rehydrate himself.*"

This showed that participants initially identified a key point to frame their problem against. In these examples the person believed that the important information to start framing their strategy against was the type of festival. They then proceeded to frame their entire strategy based around this 'anchor point'. Furthermore, some participants framed the problem using prior experiences of similar events. This was shown clearly in participant UMONPHAR1 who had never attended a music festival, but knew how many cubicles had been at their high school and the number of pupils attending the school and used the school model as a template for the number of people attending the music festival. However, although there were some successes with templating models from known situations to unfamiliar problems, many participants were unable to develop suitable templates to successfully frame the problem. For example participant UMONPHAR5 when answering problem 2 confused volume, density and weight. They created a template by using the weight of a training weight they used in the gym, and believed the volume of sweat produced to be about the same "*size [volume]*." However what participant UMONPHAR5 failed to identify is that cast iron has a different density to sweat, and therefore their template was unsuitable to frame the problem. These examples showed that despite both participants identifying and framing the problem, it was their success at framing the problem that may have impacted on the success of their strategy. The use of familiar experiences was identified by Walsh *et. al.* as a 'memory-based approach' whereby participants "*analyse the situation based on previous examples*."[326] Walsh *et. al.* suggested that participants who used the memory-based approach are unable to think beyond the variables stated in the problem and link them to the science concepts. Under this paradigm, pharmacy participants were showing characteristics associated with Walsh *et. al.*'s memory-based approach but struggled to develop suitable understanding of the problem concepts because they were unable to fit their understanding in a meaningful way to their prior experience, and furthermore think beyond their prior experiences.

Table 19 showed that most pharmacy participants were able to develop a strategy, although in some solutions their strategies were flawed. Four participants were unable to develop specific strategies for any of the problems, which were reflected in some cases as an outright guess at a solution. In these examples it was difficult to analyse the thought process and reasoning of the participant, because not much strategy was available to analyse. One aspect that seemed to impede participants' progress was how to frame the problem, which may have had some impact on being unable to develop a strategy. A common issue was understanding the context of a music festival. More than one participant exclaimed they had never attended a music festival, so were unsure how to proceed. This problem was not encountered in the other disciplines. One reason for this may have been the difference between an Australian group of participants (pharmacy) and UK participants (all other disciplines). Despite participants being at a similar education level, their life experiences may have been slightly different, which might have resulted in these participants struggling to develop a strategy. However, some participants were able to develop clear strategies for solving the other open-ended problems (N=6). As with other disciplines, the development of a strategy emerged as a series of stages rather than discrete events. This meant it was difficult to identify when the strategy was fully developed, but still possible to identify that a strategy had been developed. However, despite these six participants showing more development of specific strategies than the other pharmacy participants, there appeared to be very little difference in success at answering the open-ended problems. Table 19 identified that participants in the pharmacy cohort never developed more than one strategy to the problem. When participants fixate on a single strategy based on prior experience they were unable to develop a strategy beyond that experience. This would account for the lack of success demonstrated in Table 27 for the traffic light data.

What was of further interest was the emergence of NDIS- as a prominent code in a majority of participants. This was interesting because the NDIS- code had only emerged as a prominent code in a small number of psychology participants. The NDIS- code manifested itself in participants' transcripts by

> "*When is this festival going to held?... cause if it's in Autumn it would be different to others, and if there is food and whether it is held at night*" and "*well I guess a lot [of toilets] but what would be… is there a right or wrong answer? I mean how much is it going to cost cause that's got to be considered by the organisers*."

This showed that when pharmacy participants were identifying the problem and framing what was being asked they became distracted and side tracked from actually solving the problem. This could be because the participant was unable to construct a meaningful or robust template to develop a strategy because of the missing information or over complicated the model they had created.

Table 19 showed that as a discipline, pharmacy participants were not consistent in their ability to use a logical and scientific approach, with some participants showing a logical and scientific approach for some problems and not others (e.g. UMONPHAR13). For the most part participants who were unable to develop a logical and scientific approach guessed at a suitable solution, providing no scientific background to how they arrived at the answer. Camacho and Good suggested that successful problem solvers used "*several principles and related concepts to justify their reasons,*" whereby participants were able to ground all the processes in scientific principles.[346] It is unclear from Table 19 why participants could use a logical and scientific approach for some problems and not others, nor was it identifiable in the transcripts why this was the case, although, it may be due to the inability to develop models beyond their experiences and, where a problem is beyond their experience, they were unable to apply scientific principles. Previous literature is unable to support further the lack of logical and scientific approaches observed in pharmacy participants.

Becoming confused with the problem and lacking confidence in their ability emerged strongly in pharmacy participants, with many becoming confused with the problem. The lack of confidence in their own ability materialised in participants with comments such as "*I'm making estimations here, although I'm not sure whether those are the right numbers at all*". As can be seen in this example, participant UMONPHAR10 lacked confidence in their ability to make estimations and approximations. However, despite this, they proceeded with these values to ensure they could complete the task. Participants also showed signs of confusion with the problem through comments such as, "*hmm, I'm not sure now, I'm gonna have to stop and think*" and "*Is that 5% the volume in air or is the volume in the lungs… hmm that's not very helpful*". In both these examples the participant was struggling with the parameters of the problem. In the first example the participant had to tell themselves to stop and think more about the problem, because they were becoming confused by how to approach problem 3. The second example showed the participant struggling to understand the meaning behind a piece of specific information. The participant was conflicted with how to use that piece of information before eventually they continued to develop a strategy. Table 19 showed that two participants did not become confused with the problem. Those participants were UMONPHAR4 and UMONPHAR14. Participant UMONPHAR4 showed no signs of lacking confidence with their ability or becoming confused with the problem. However, the participant used flawed strategies throughout their solutions, and was unable to reflect on their strategy. It may be possible that participant's false sense of confidence may have resulted in their low traffic light score as shown in Table 27, however it was more likely due to flawed strategy development. The other participant UMONPHAR14 showed a mixture of confidence and confusion in their strategy. However, they lacked confidence and became confused with just problem 1. As discussed previously, participants were unable to develop a suitable strategy to answer problem 1 because, in part, of an inability to contextualise their knowledge about music festivals having never attended a festival themselves. This further supported the literature by Walsh *et. al.* who suggested that participants using a memory based approach fixate on their prior experiences.[326]

The individual profiles for pharmacy undergraduate participants showed a wide variety of different approaches, although all participants showed a prominent emergence for IPF+ and many showed a high distribution for IIN+.

The pharmacy undergraduate participants can be categorised into three separate groups based on the data presented in Table 19. These three categories are 'all positive', 'low negative (one or two highlighted negative approaches emerging from their profile) and 'high negative' (many highlighted negative approaches emerging from their profile) similar to the profiles emerging in Overton *et. al.*[316]

There were four participants that used only positive approaches; UMONPHAR1, UMONPHAR2, UMONPHAR10, and UMONPHAR11. There is a large amount of commonality between these participants because they all showed IPF+ and IIN+ as a prominent approach, however other positive codes emerged with some ‘all positive’ participants such as ALG+ in participants UMONPHAR1 and UMONPHAR10. This was interesting because although they showed signs of all positive approaches their radar profiles in Figure 30 and Figure 31 appeared quite different. In the first instance participants UMONPHAR1 and UMONPHAR10 looked very similar to the physical sciences participants, yet the profiles for participants UMONPHAR2 and UMONPHAR11 looked quite different. Overton *et. al.* suggested that participants that show predominantly positive codes had greater expertise than those participants who show predominantly negative approaches.[316] Participants in the ‘expert’ group under the Overton *et. al.* model were able to develop logical strategies, make estimations and evaluate their solutions. However, these participants did not show the same characteristics despite showing predominantly positive approaches. Although these participants may have been considered to have greater expertise because they showed more positive approaches, it was not reflected in Table 27 for the traffic light data.

There were three participants in the ‘high negative’ group with some positive approaches. These participants are UMONPHAR4, UMONPHAR8 and UMONPHAR14. There was no commonality in the highlighted approaches for these three participants, nor did the radar chart profiles in Figure 30, Figure 31 and Figure 32 identify similar shapes for these three participants. Overton *et. al.* suggested that participants who show a mixture of positive and negative approaches are transitional in their expertise and were able to evaluate their solutions, but still seek an algorithmic approach. However, these participants in our study did not all seek an algorithmic approach or evaluate their end solution.

The remaining seven participants were in the in the ‘low negative’ group which showed a few negative and some positive approaches. These participants were not very similar to each other. Most of the participants in this group showed NDIS- emerging as prominent, however this was not always the case (UMONPHAR7 and UMONPHAR11). These participants would also be considered transitional under the Overton *et. al.* definition,[316] with the same limitations associated with the high negative approaches group. However, when the data was compared against the traffic light data in Table 27, these participants had low success at solving open-ended problems and must be classified as novice problem solvers, despite showing characteristics that would place them as transitional under the Overton *et*. *al*. paper.

As a discipline, Table 19 showed that pharmacy participants focus their approaches towards IIN+, IPF+, NDIS-. This showed that pharmacy as a discipline exhibited some of the same approaches as those in the physical sciences, but with the addition of NDIS-. Figure 32 showed that the profile of positive codes in the overall radar chart for pharmacy looked very similar to those for the physical sciences, displaying the angular formations along IIN+, IPF+ and ALG+. However, the negative coded approaches did not look similar to any other profile especially with the prominence of the NDIS- approach. This may be a pharmacy specific characteristic whereby participants from pharmacy required prior experience to help them with the missing information, and when they were unable to template these experiences they became distracted by the missing information. One suggestion could be that the degree programme for pharmacy is very context specific meaning pharmacy participants are too reliant on prior experiences and the context in which those skills are learnt. This would explain participants' insistence on templating their experiences to solve these open-ended problems.

6.6 Approaches Exhibited by Chemistry Academic Participants

A vast amount of literature explores the differences in behaviour, cognitive ability and performance between 'expert' and 'novice' problem solvers, especially in chemistry, physics and generic problem solving. In particular interest is the work by Larkin *et. al.*[181], Overton and Potter[316] and Bilalić *et. al*.[173]

Chemistry academic participants all showed prominence at identifying the information needed for the problem, as shown in Table 20. As with the other disciplines, academics identified the information needed in two specific ways; as an additional framing and developing a strategy, and asking for information in order to continue their chosen strategy. An example of a chemistry academic showing identifying the information needed as an additional strategy to frame the problem can be seen in participant EXST1 who following a framing of the problem stated "*So do we have any of that information? So the circumference of the wheel perhaps.*" The participant continued to probe the interviewer for information by asking "*do we have the rate of erosion of the tyre.*" Once the interviewer repeatedly informed the participant they did not have access to that information participant EXST1 stated "*doesn't really matter what an atom thickness is without the other information. So one has to think of an alternative.*" This example clearly showed the participant is using identifying the information as an additional framing stage to the problem, and furthermore to develop a strategy. Some academic participants asked for information in order to continue a strategy they had already chosen. This can be seen in participant EXST2 whilst solving problem 3 who chose to calculate the mass of the atmosphere using volume and density. Part way through their solution the participant had calculated the volume of gas in the atmosphere, but was unsure about the density stating, "*I would calculate the volume of this sphere right, which is the radius cubed. Now then if I had the density I would calculate… do I have the density?*" In this example the participant had clearly already chosen the strategy they want to use, and had asked the interviewer for a specific piece of information in order to continue their chosen strategy.

Making approximations and estimations appeared common in academic participants, with Table 20 showing five participants who showed prominence. Approximations and estimations emerged in academic participants in two different ways. Firstly, participants used estimations and approximations to maintain the momentum of their strategy. Normally this followed a participant asking for information which the interviewer was unable to provide. An example of this can be seen in participant EXST5 who stated "*Roughly how big is a tyre. It's about… 40 cm across, is that a reasonable estimate.*" In this example the participant was estimating the radius of a tyre to be 40 cm, directly following asking the interviewer "*how large the tyre would be.*" A further example was a participant estimating the data without asking the interviewer for the data first. An example of this could be seen in participant EXST3 who after a framing stage stated, "*lets assume that 50,000 people could go, ok what would be a sensible ratio of people to toilets.*" The participant in this example had a clear idea of how to approach the problem and preferred to use estimations rather than ask for specific information. Overton *et. al.* investigated undergraduate chemistry participants and identified that participants who showed mainly positive approaches were considered experts, and had the ability to make approximations and estimations. Table 20 showed that in our study we were observing the same characteristics as the Overton *et. al.* study, with only one participant not using approximations and estimations.[316]

Academic chemistry participants made calculations and used equations (ALG+) in a very similar way to their undergraduate and postgraduate counterparts, whereby participants made both calculations and used specific equations. Table 20 showed that ALG+ was a prominent approach in four of the participants in this cohort, with other members of the group showing signs of its emergence. The same specific equations emerged in the academic participants as the chemistry undergraduate participants, with participant EXST1 writing Vol Sphere = $\frac{4}{3}\pi r^3$, and calculating the mass using density = $\frac{mass}{Volume}$. Table 20 showed that academic participants were using algorithms and equations throughout their problem solutions. However, Table 20 also identified that some participants do not use algorithms and calculations at all in some solutions, for example participant EXST2 never showed the ALG+ code in problem 1 and 2. This would suggest that the participant preferred to verbally and qualitatively estimate their answer instead of making specific calculations.

Evaluation was an approach which emerged in all participants, however was prominent in only four participants. One example of evaluation was observed in participant EXST1 who stated, "*does that sound about right? Is my maths correct?*" In this example the participant is reflecting on how they had answered the problem and the answer to their problem. However, unlike other reflective comments, the participant then proceeded to recalculate their answer to ensure they have followed their strategy correctly. A further example of evaluation was observed in participant EXST7 stating, "*that's a little bit* *excessive, I think I have gone wrong somewhere, I know that is not right. I've lost where I am going now.*" In this example the participant was less sure on whether the processes they had employed were correct to solve the problem. However, the participant then continued, "*That's what I was doing, the decimal point in my calculation. I was giving was completely correct but my calculation here is some what rubbish.*" The participant in this example pauses once they had identified that something was wrong with their calculations instead of blindly believing the processes they had previously completed as being correct. The participant identified the specific problem with their calculation and then proceeded to rectify this problem. Overton *et. al.* identified that participants that used more positive approaches were able to evaluate the problem.[316] When the data presented for evaluation in our study was compared against the timeline data in Table 38 it could be seen that evaluation may not be a pre-requisite for success. In some participants it certainly supported their approaches and allowed them to achieve greater success, however, it was not essential for success. Walsh *et. al.* also suggested that evaluation was not present in unsuccessful participants.[326] However Table 38 clearly identifies that this was not the case. Specifically participant EXST7 used evaluation in both question 2 and 3 and yet still scored a red solution under the success criteria. So although Walsh suggests that no evaluation is present in unsuccessful problem solvers, our study would refute that having identified the contrary.

Identifying and framing the problem was shown in Table 20 as being prominent in four participant's profiles. Furthermore, all participants showed use of identifying and framing the problem (not a prominent approach but still present). Participant EXST1 showed identifying and framing the problem by stating, "*Yeah, so to determine the number of toilets required at a music festival* *we need to have an idea of the number of people.*" In this example the participant clearly identified a needed parameter for solving the problem. Although the participant was identifying the information needed, identifying the specific piece of data informed the identity of the problem, and therefore identified what was being asked. A further example is seen in participant EXST8 who stated that "*you have a problem if you take a column of atmosphere, it's denser down the bottom than the top, so you can work out the volume of that corridor…*" The participant in this example was redefining the parameters and limitations of the problem, interpreting how to develop a strategy to solve the problem, thinking about the atmosphere in smaller pieces rather than an entire atmosphere. Chi *et. al.* discussed that physics participants who showed more expert like behaviour analysed the problem qualitatively before attempting to solve it.[185] Our study was unable to identify the presence of this characteristic. When comparing identifying and framing the problem with the traffic light codes presented in Table 27, participants that showed high percentage for identifying and framing the problem could have scored a variety of traffic light scores. Four participants who did not show prominence for IPF+, scored lower than other participants who did show prominence of the IPF+. Although this appeared to support the trend observed in Chi *et. al.* it should be noted that the approach was observed still in participants that scored low for the traffic light data. Furthermore Chi *et. al.* only identified the physics principles as qualitatively framing the problem, whereas for participants in our study IPF+ was more encompassing.[185] This may account for the differences in the observed trends.

Most of the participants in the chemistry academic cohort were able to develop a specific strategy to solve their problems (DAS+). Table 20 showed that some participants were able to develop multiple strategies for their solutions, in particular participant EXST7 who directly stated "*let us approach this from a different angle,*" showing they were actively seeking an alternative strategy to the one they previously employed. Using multiple strategies with one problem was not observed in undergraduate participant cohorts. As with the undergraduate participants, it wasn't possible to identify specific events that resulted in the development of a strategy, just that particular strategies had been developed.

A majority of chemistry academic participants were able to solve open-ended problems without becoming distracted by the lack of information (NDIS+). However, Table 20 showed that two participants did become distracted by the lack of information (NDIS-). An example of this is shown by participant EXST8 who stated

> "*the tyre will be constructed of a rubber compound, and no doubt they are constructed so they don't wear emmm so for an individual tyre or make of tyre you would need data on how quickly it degrades.*"

In this example, the participant was hypothesising that in order to answer the problem extra data about the tyre ware was required. The participant continued by stating "*that there is no way of knowing the rate of degradation without having some sort of look up table or some experiments.*" Both of these examples demonstrated that the participant was unable to think about the information required to solve the problem themselves, instead favouring to identify how they would acquire the data they required. As such they became distracted by the lack of information in the problem, and were unable to move beyond that. Overton *et. al.* suggested that participants that used predominantly negative approaches suffered poor success when the becoming distracted by the lack of data and lack the relevant background information.[316] This was not always the case in our study. In fact Table 38 showed that participant EXST6 was distracted by the lack of information at the beginning of question 2 and still has great success. Furthermore, participant EXST7 showed no signs of becoming distracted by the lack of information, and yet was still unsuccessful. As such it is hard to support the claim by Overton *et. al.* through our data that becoming distracted by the lack of information creates an unsuccessful approach.[316]

Chemistry academic participants, as shown in Table 20, showed low instances of lacking a logical and scientific approach. Only two participants showed lacking a logical and scientific approach (LSA-). In both these examples the participants (EXST1 and EXST3) outright guessed at an answer based on a gut feeling which had little grounding in scientific reasoning. Participant EXST3 stated that they "*made an assumption that you would require one toilet per 50 people and therefore the answer comes out at a thousand.*" Although the ratio maybe appropriate, the participant did not reason why this was the case. Participants in the chemistry academic cohort who used logical and scientific approaches (LSA+) clearly demonstrated systematic methods to solving the problems and using scientific reasoning behind the decisions they made.

Table 20 showed a variety of behaviours emerging with respect to confidence and confusion codes, with some participants showing high levels of confidence (n=2), and others showing a mixture of lacking confidence in their ability and becoming confused with the problem (n=2). Most participants showed confusion with the problem (CCP-). An example of this was seen in participant EXST3 who stated, "*I've got no feel for how I could work out the* *number of moles involved which would then allow me to calculate weights. I'm not seeing how to connect that to any of the other information I've got.*" In this example the participant had clearly reached an aspect of their strategy where they know what they have achieved and where they want to go, but are unsure how to bridge the two ideas together. Although this might be construed as lacking ability, the example here was specific to the problem. A further example could be seen in participant EXST5 who stated, "*Mass of atmosphere? The whole thing, the whole planet… Atmosphere, mass. Oh this is a bit harder.*" In this example the participant was at the initial stages of engaging with the problem and is confused how to even begin solving the problem. Participant EXST5 also showed prominence at lacking confidence in their own ability, which was shown by them stating "*I should be able to add that without a calculator – shouldn't I.*" In this example although the tone of the comment was delivered tongue in cheek, the participant was concerned in their ability to add to values together. This characteristic was also observed in many of the undergraduate participants, although this was not represented in the think aloud data from Table 20. However, it did emerge in undergraduate participants using the calculator for a majority of their calculations, even with simple addition processes.

The individual profiles for academic participants showed that a majority of approaches used are positive. The academic participants as a whole appear to focus on the IIN+ code (identifying the information needed) in conjunction with the IPF+ code (identifying the problem and framing) and ALG+ (making calculations and using algorithms), although this behaviour was not present in all participants. Under the Overton *et. al.* definition, participants that used predominantly positive approaches were expert problem solvers.[316] The traffic light data in Table 27, which showed that academics scored the highest average for solving their three problems than the other participants in the study, supported the claim that greater success emerged from more positive approaches. However, individuals using mainly positive approaches were not a predetermination of success at solving open-ended problems in chemistry academic participants. It has long been identified that understanding how problem-solving strategies developed play a key role in acquiring expertise.[173, 174, 176, 177, 179, 182] De Groot asked chess players of varying ability to solve the same problem, and captured the data through a think aloud protocol. De Groot identified that experts showed no superiority in planning their strategy in advance. This was further supported in the literature by Smyth *et. al.*[359] and Sternbeg and Ben Zeev.[360] Our study would support these claims for problem solving in open-ended problems, whereby chemistry academics appeared to use identifying and framing the problem no earlier than the less expert undergraduate participants (Table 14 and Table 15). Larkin *et. al.* reported that often differences between individuals who have more expert like behaviour than novice were relying on discipline 'intuition', and as a result were able to solve problems quicker than novice problem solvers.[181] When we compare the 'expert' like behaviour as defined by Overton *et. al.*[316] it was clear that for open-ended problem solving, the speed at which the problem was solved had no relationship to the expert like behaviour (Table 37) Furthermore, the speed at solving the problem had no relationship on the success at solving the problem. Larkin *et. al.* further stated that discipline specific knowledge was a prerequisite for expert skill, and that those participants who have this prerequisite are more successful at solving problems.[181] Our study had identified that academic problem solvers were more successful than undergraduate problem solvers. Even though our problems were designed so that A-level students should be able to tackle them, the extra disciplinary knowledge possessed by the academic problem solvers may have contributed to their greater success. However, this extra knowledge did not emerge in our study otherwise it would have been coded separately as an emergent theme. Because this didn't emerge as a theme it may mean that solving open-ended problems, may not require as much dependency on prior knowledge, and as such less reliant on pre-developed schemata.

Participant EXST3 was different from the other participants in that they showed an inability to make suitable approximations and estimations to ensure the development of their chosen strategies. This was reflected in Figure 33 where the participant showed little emergence of ALG+ or A&E+. This was unusual when compared against other chemistry academic participants because participant EXST3 had shown a very large prominence towards identifying the information needed, meaning they were comfortable asking the interviewer for details, yet not comfortable to generate their own data. This reflected what happened in their solution, whereby participant EXST3 tried to frame the problem by asking for multiple sources of data from the interviewer whilst answering the problems. However, when information was not available the participant was unable to adapt their approaches being reluctant to make approximations and estimations. This resulted in a stalled strategy.

Table 20 showed that academic participants as a cohort employed a majority of positive approaches. However, they used predominantly identifying the information needed, framing the problem and making calculations and using equations, which were very similar to the physical sciences participants. There were however, less representation of codes as a discipline than there were as individuals, with only three codes (IIN+, A&E+ and ALG+) highlighted in light grey in Table 20. This would suggest that a wider number of approaches were used by individuals then are apparent as an overall discipline. However when the secondary coding approach shown in Table 24 is completed it was clearer to see the wider use of approaches used for the chemistry academic cohorts. The radar chart for the academic cohort from Figure 34 had a more rounded structure than the undergraduate chemistry participants (Figure 18), although the shape was representative of the values seen in Table 20 for the 'academic: % distribution of overall approaches.' The more rounded shape of Figure 34 showed that a wider number of approaches were used by the chemistry academic participants, than the undergraduate chemistry participants, which was supported via the secondary coding in Table 24. The lowest three codes identified in the expert participants were IIN- (does not identify the information needed), IPF- (unable to identify the question or frame the problem) and DAS- (develops a strategy).

Table 27 identified the level of success where one would expect participants that showed more expert like behaviour scoring higher than participants who showed more novice like approaches. However, what was observed, and has been discussed throughout this section, is that the data in Table 20 when compared against Table 27 showed that participants were able to show more expert like approaches, whilst still varying success at solving open-ended problems.

6.7 Approaches Exhibited by Industrialist Chemistry Participants

No literature was found that related to graduates working in industry solving any type of problem. As a result of the lack of literature, comparisons will be drawn against expert novice literature as discussed with the chemistry academic participants.

The emergence of identifying the information needed is observed through participants asking "*how many tickets [will be sold]. Are you able to furnish me with that information*" and "*knowing what altitude you'll be going to when there is still an atmosphere or how high you can go before there is no atmosphere.*" Both these examples were used by participants during the initial framing stages of problem solving as a method of focusing their approach. Other examples of IIN+ were asking for specific pieces of information once the participant had decided on a particular strategy, normally once they had commenced their chosen strategy. An example of this was deciding the formula $density = \frac{mass}{volume}$ was important for calculating the mass of the atmosphere. In this instance participant EXST10 asked for "*the density of the atmosphere.*" This piece of information was also asked for by participant EXST11 who said "*do we know the density of the atmosphere.*" In both of these examples the information could be provided to the participant, and as such they did not have to alter their preferred strategy for problem 3. Identifying the information needed, as shown in Table 21, emerged as a prominent approach in all participants, ranked as the highest percentage approach in four participants.

Chemistry industrialist participants used approximations and estimations usually after asking the interviewer for information, with Table 21 showing all but one participant had used the approach. The approach had been observed in participants EXST12 who stated "*the average visit is going to be, lets say the men are going to take two minutes and the ladies double that.*" In this example the participant had been previously struggling to frame the problem because of the lack of information, however the participant wanted to ensure that their strategy did not stall, and so estimated the length of time of a toilet visit. A further example of making approximations and estimations can be observed in participant EXST14 who stated "*assume the wear rate is. I want the wear rate in millimetres per mile… so assume a similar rate of wear so that is one over ten thousand millimetres per mile.*" This example of an estimation for the rate of wear was based on the participant's own experience with their car, and was derived to ensure the strategy continued. As previously stated one participant, EXST13, made no estimations and approximations and was reluctant to make estimations where concrete evidence was not provided. The participant instead preferred to stipulate how they would gather the information they lacked. The preference to suggest a method of collecting the data, had only been observed once before in a chemistry academic participant. However that participant had made estimations to eventually develop a solution.

Making calculations and using equations emerged in four industrialist participants as a prominent approach. Table 21 showed that participants from industrial chemistry rarely showed the ALG+ code towards the beginning of solutions, and was not used in every solution. An example of this is seen in participant EXST10 who showed no calculations or use of equations in both problem 1 and problem 2, but used calculations and equations in problem 3 eight times. An example of a participant using equations and making calculations can be seen in participant EXST14 who used the equation $\frac{4}{3}\pi r^3$. This was a very common equation amongst all disciplines who had this question, and was frequently identified as an appropriate equation to use. A further example can be observed in participant EXST12 who wrote down a variety of equations in an attempt to develop a strategy, including $2\pi\mathrm{r}$, s =d/t and $2\pi r/t$ toying between ideas of revolutions per unit time and the use of speed to calculate their answer. Eventually the participant altered their approach towards a rate of wear over the lifetime of the tyre.

Evaluation was an approach shown by chemistry industrialist participants, although it was not prominent as seen in Table 21. Industrialist participants use evaluation in a variety of ways, although principally it was observed from the middle and at the end of their solution as Table 39 showed. This meant that some participants were evaluating as they proceeded with their strategy, and others were principally evaluating their end solution. A participant who evaluated their strategy whilst engaging in the problem was participant EXST13, who for problem 3 stated "*We know that a mole of a given gas will occupy a certain volume and so therefore we know what the weight is of that specific volume. I think we have all the information we need there to do it.*" This participant had developed a strategy and knew how they want to proceed with the problem after they had assessed whether they had all the information they needed. Many participants evaluated their final solution. However participant EXST12 evaluated their calculations as they proceeded with the problem stating, "*So I want to divide one hundred and fifty thousand by twenty four. Is that right, hmmm, hang on. No I'm talking rubbish, that's divided by sixty first.*" This example showed that participant was evaluating their solution as they make their calculations to ensure they were using the correct mathematical processes.

Chemistry industrialist participants attempted to contextualise the problem by identifying and framing the problem. As Table 21 showed, identifying the information needed emerged throughout a participant's solution, not just towards the beginning. An example of identifying and framing the problem emerging towards the beginning of a solution can be seen in participant EXST9 who stated "*the faster you will go the more wear will take place, so I would suggest I would do constant speed. although that is not real.*" In this example the participant was suggesting a model to help them understand the problem. The participant was aware that cars travelled at variable speeds, because of the initial statement suggesting faster speed would result in greater tyre wear, but acknowledged that a constant speed would be an easier model to work with. As Table 39 showed, participant EXST13 used identifying and framing the problem throughout their solution and in problem 3 used identifying and framing the problem as their final approach. This was because the participant was running out of time, and wanted to express to the interviewer how their understanding of the problem had developed from the initial stages, they were just incapable at executing their plan.

Table 21 showed that, generally, industrialist participants were able to develop a strategy when solving open-ended problems, with only EXST13 struggling to do so. As with all other disciplines the emergence of developing a strategy occurred as a series of events rather than at a single point. This made it difficult to identify when participants had their 'eureka' moment with strategy development. As identified in the results section, industrialist participants did not all use the same approach when answering the problems. What was interesting was that, unlike some of the chemistry academic and physics undergraduate participants, industrialists developed a single strategy and focussed their efforts on that strategy. This meant that when their strategy was flawed, they were unsure how to alter their approach, or recognise the flaws in their strategy. Participants rarely verbalised a specific strategy , however, participant EXST12 stated that "*so it's just a case then calculating the volume of two spheres and* *subtracting one from the other and timesing the difference of that by the density.*"

Becoming distracted by the lack of information was not common, although it did emerge in all participants. Table 21 showed that some participants became easily distracted by the lack of information, and was seen in participant EXST10 who stated "*I would say that I would need more facts about what the regulations are and how often you need to empty them, so I would say in the region of about 500 [toilets]*" This participant showed they were unable to develop a suitable strategy because of the lack of information. This meant that the answers they provided were actually a guess, rather than grounded in scientific reasoning. Participant EXST10 was too distracted by lack of data to develop a logical and scientific approach.

For the most part, chemistry industrialist participants were able to develop a logical and scientific approach. However, they stuck to a single strategy, unable to identify their strategies flaws. This was observed in participant EXST9 who identified the parameters that they had available to them before trying to identify a work-around for the data they lacked. This was observed in other participants, in particular participants ULEIISCI3 and EXST8. This may possibly have been in part due to participants not considering that the approach required needed to be scientific or logical because it did not have a scientific context.

Table 21 identified that industrialist participants often became confused with the problem and lacked confidence in their ability. All participants showed a prominence of a confusion or confidence code, with three participants showing they both lacked confidence in their ability and became confused with the problem. Participant EXST9 clearly showed signs of lacking confidence in their ability by making statements such as "*I'm going to embarrass myself now… I don't do sums anymore*" In this example the participant was clearly questioning their ability to perform mathematical processes. A further example can be seen in participant EXST12 who stated "*Even I don't need a calculator for that… is it right?*" In this particular example the participant entered the phase with what seems to be confidence, however that quickly dwindled when the participant checked whether they were correct with their assumptions This lack of confidence in their ability emerged again when they stated "*Oh I wish I didn't have to do all this maths… cause now I'm think how do I deal with those exponentials.*". Although some participants lacked confidence in their ability to answer the problem, it did not seem to impede their ability to develop a strategy nor to make progress with their solution.

The individual profiles for the industrialist participants were very similar to each other, with all participants showing prominence in IIN+ and IPF+ (Table 21). Some of them showed highlighted approaches for ALG+, with those participants where the code was not highlighted still showing moderately high percentage distribution towards that approach.

Table 21 showed that industrialist participants as a cohort favoured a majority of positive approaches IIN+, IPF+ and the ALG+ codes, which was very similar to the physical sciences participants shown in Figure 18 and Figure 22, in particular the chemistry undergraduate participants. The lowest codes identified in the industrialist participants were IIN- (does not identify the information needed), IPF- (unable to identify the question or frame the problem), DAS- (does not develop a strategy) and LSA- (illogical and none scientific approach)

The shape of the profile in Figure 35 for participant EXST13 showed much less A&E+ (0%) than the other five participants. This was shown in their solutions when the participant was unable to obtain the information they needed, not through lack of trying (IIN+ = 28.03%), they resorted to developing a template where they thought they would be able to acquire the information they needed. In each problem the participant hypothesised how they would conduct research to acquire the information that they needed, but refused to commit to a strategy. Furthermore, for problem 1 and problem 2, the participant was unable to make calculations or use algorithms (ALG+) because they were unable to identify the equations they might need or the values they needed to develop a numerical answer. However once the participant could access the information they needed, they are able to adopt a more algorithmic approach, which was reflected in the slight emergence of the ALG+ code in Table 21. For a period of time the participant was able to process the problem; that is until again they encountered a lack of information. Once participant EXST13 encountered a blockage in their chosen strategy, they were again unwilling to commit to making estimations and approximations, despite having the foundations of a good template. This is reflected in Table 27 where the traffic lighted success for participant EXST13 is lacking in comparison to the other industrialist participants. In this case the participant's lack of success is based on an inability to adapt to the different problem, reluctance to estimate suitable values for missing information and lack of ability to transfer previous knowledge to a new template for understand a new situation. This mirrored the lack of success by EXST3 in the academic participants group (Figure 33) who once their strategy encountered similar blockages was unable to continue which was represented in the lack of A&E+ and ALG+ in their radar chart profile.

6.8 Approaches Exhibited by Postgraduate Chemistry Participants

Some literature exists looking at the performance and approaches used by postgraduate students. Of particular interest is the literature produced by the Bodner research group, who have looked at postgraduate approaches using think aloud protocols. Because postgraduate participants are transitioning between undergraduate novices to experts in their specific field of research, comparisons will also be drawn against expert/ novice literature such as Larkin *et. al.*,[181] Overton *et. al.*[316] and Bilalić *et. al*.[173]

The postgraduate chemistry participants showed two different ways of identifying the information needed (IIN+), with all participants identifying the information needed and three participants showed prominence (Table 22). As with other participants, postgraduates identified the information as part of identifying and framing the problem. This was seen in participant PGHULL1 who asks "*how many people go to the music festival?*" In this example the participant was asking for this specific information to begin framing the problem. Furthermore, the timeline data shown in Table 40 identifies that IIN+ was the first code in a majority of postgraduate participant's solutions. This clearly showed that participants were using IIN+ as an additional step in identify and framing the problem. Some participants asked for information whilst solving the problem. In particular participant PGHULL2 who asked for "*Avagadro's number,*" whilst solving problem 3. This example was shown in Table 40 as being deep into the participant's solution and emerged once the participant had developed a clear strategy. A similar example was PGHULL1 who stated "*I am trying to think how tall the atmosphere is. Do you know how big the atmosphere is? How high is the atmosphere?*" In this example the participant had approached the point in their strategy where they needed the additional information to continue.

All chemistry postgraduate participants made approximation and estimations in their solutions, most often towards the beginning of their solution. However Table 22 showed that only two participants showed prominence for this approach. An example of this is shown by participant PGHULL2 who estimated the volume of waste held by a festival toilet to be "*100 litres of waste.*" The same participant also stated that they would "*go for 2 litres of waste produced by one person per day.*" Despite the interviewer being unable to provide these details the participant was prepared the make estimations to continue the momentum of their strategy. The same participant repeatedly used estimations and approximations during problem 2.

Chemistry postgraduate participants used equations and made calculations and three participants showed prominence for the approach. Participant PGHULL1 used a specific equation in problem 2 where the participant stated that the "*circumference equals pi times [the] diameter.*" The same participant identified that problem two required equation Volume $=\frac{4}{3}\pi r^3$. In both of these examples the participant showed clear understanding of appropriate mathematical equations required for solving the problems. Participant PGHULL5 showed the highest distribution for this approach (Table 22), and made calculations throughout their solutions. Table 40 showed that these participants used ALG+ approach throughout their solutions suggesting that they preferred to answer these open-ended problems through numerical reasoning rather than verbal reasoning.

All participants engaged in some aspect of evaluation, although as Table 22 showed, the amount of evaluation varied between participants. Participant PGHULL1 showed only one example of evaluation and "*oh no I have forgotten to cube everything. I thought it was a bit small… That's much better.*" Unlike the undergraduate participants, this participant identified a specific problem with their solution and then addressed that specific issue. When evaluation emerged in the undergraduate students there was a vague understanding the solution was wrong, rather than a specific understanding. Participant PGHULL5 showed the most amount of evaluation, and in particular question 3 where the participant stated,

> *"Ok, so I will assume a density, because I wont get into all the mathematics of it otherwise I will be here all day" and "Is that, oh, lets stick with the weight, cause it's not quite centimetres cubed is it… so we've got the weight per mole, yeah, that's what I want."*

In these examples it was clear to see that the participant was evaluating their strategy throughout their solution. In the first example the participant was showing they understood the importance of limiting the complexity of their model so that they could complete the problem they were solving. If the participant had not assumed a density, they were of the belief that it would make their model too complex, and they would be unable to complete the task due to lack of ability and time restraints. The second example showed the participant evaluating their answer for a particular stage of the problem. In this example they were ascertaining the units of the value they have calculated, this pause in the process although at first appearing innocuous ensured that the participant's chosen strategy could continue without stalling.

Postgraduate participants in chemistry identified and framed the problem, with Table 22 showed that three participants showed IPF+ as a prominent approach. They showed identifying and framing the problem in two similar ways as undergraduate participants. The first way in combination with IIN+ approaches could be seen in participant PGHULL1 who stated "*well how big is the wheel? Oh my god. I'd go with just one rotation. Do I need to give a specific number?*" In this example the participant has discussed how to approach the problem and whether their assumption would be sufficient to answer the problem. A further example was seen in problem 3 where they stated

> "*can it be an ideal gas constant thing? So the atmosphere contains oxygen, o two, n two, c o two and bit of other stuff… Volume of the atmosphere is. I don't know, how big's the earth.*"

In this series of statements they were clearly redefining the parameters of the problem outside of those stated in the original question. As a result the participant was developing a more complex model for the problem.

Table 22 showed that no participant was unable to develop a strategy (DAS-). As stated in the results section, participants were able to develop a variety of solutions to the problems, although no specific event could usually be identified as to when the strategy was developed, just that a particular strategy was developed. However, participant PGHULL5 directly described the strategy they were going to develop stating, "*so what we need to do is calculate the volume of two spheres and subtract one from the other. Don't you.*" In this example the participant clearly defined the strategy they intend to use when solving problem 3. The exact point when the strategy was realised by the participant is difficult to identify as with all disciplines. In all participants, the strategy developed over the whole solution was possible to identify that a strategy was developed.

Some of these participants became distracted by the lack of information (NDIS-), as shown in Table 22. What was interesting is that the distraction related to specific points in the problem, rather than the overall problem. An example of this was in participant PGHULL3 who stated

> "*does toilets include toilets and urinals?…so how spaced out would the toilets be in, would they be in one area? So I'm going to go with one toilet per thousand people and make people wait.*"

In this example the participant was struggling to obtain information they think they required, which resulted in them guessing a ratio of 1000 people per toilet as a direct result of being unable to obtain the specific pieces of information they required. A further example of becoming distracted by the lack of information was seen in participant PGHULL5 who, for question 2, stated when asked if they were happy with their solution, "*yeah, well as happy as I can be. Well I'm not happy with it but I am given the assumptions I have made.*"

For the most part, postgraduate participants in chemistry were able to develop a logical and scientific approach to solving open-ended problems, but Table 22 showed some participants struggled, such as participant PGHULL2 who struggled to develop a systematic and logical approach for problems 2 and 3.

Lacking in confidence and becoming confused seemed common amongst postgraduate chemistry participants. Most participants showed both a lack of confidence in their ability and became confused with the problem at some stage. However, four participants showed prominence with becoming confused with the problem. An example of this was seen in participant PGHULL2 who stated

> "*Right, now we'll say 20% of the volume is the atmosphere not the actual earth. Just a wild guess cos I've got no real idea. It depends when you judge when the atmosphere ends.*"

In this example the participant showed a lack of confidence in how they had estimated the percentage volume of the atmosphere. A further example can be seen in participant PGHULL3 who stated "*so there are eight atom layers I think, so nought point one into one centimetre. Hmm, that's not right. Would that be nanometres? So that's 80 layers. Maybe.*" An example of this can be seen in participant PGHULL2, who when the interviewer asked the participant if they were happy with their solution they stated "*not in the slightest.*"

The individual profiles for postgraduates have some similarities but may not be considered the same as each other. As such, it was difficult to build a profile based on the data in Table 22 alone. However, once the data is analysed in Figure 37 three profiles emerged from the data.

PGHULL1 and PGHULL3 (Figure 37) showed very similar shapes to those of the chemistry undergraduate participants (Figure 16, Figure 17, and Figure 18). These two participants showed elongations along IIN+, IPF+ and ALG+, displaying the angular characteristics commonly seen in physical science undergraduate students. The characteristics for IIN+ normally exhibit themselves by asking for "*how many people are attending the music festival?" and "how thick is the one atom layer?*" These appeared to be typical pieces of information participants asked at the beginning of the problem, as an additional method to frame the problem whilst they decided the best strategy to answer the problem. This was a characteristic also observed in physical science participants, presumably under the initial assumption that if the interviewer had those details then it must be an important piece of information. However, unlike the undergraduate physical science participants, the postgraduate participants after a short period of probing for additional information, proceeded to estimate the information themselves in order to develop their strategy and solve the problem. This was observed for participant PGHULL1 who, once they had identified the information they needed, quickly established a strategy regardless of whether the interviewer was able to provide that information. For example, during problem 2 the participant assumed one revolution of the tyre would be sufficient to remove a one atom layer, from that stage the participant proceeded to ask for "*how big is the wheel,*" and once they were told that information was not available, then they were happy to estimate a value and calculate the circumference. The participant was certainly using identifying the information needed to frame their strategy before commencing with the problem, but was not easily confused by the lack of information provided to help them frame the problem.

For PGHULL2 and PGHULL4 a different profile emerged from the data (Figure 37), in that they displayed elongations along ALG+ and A&E+ instead of along the IIN+. Differences emerged with these two profiles in that they did not share similar distribution along the IPF+, however within these two profiles the main characteristic was the shift from IIN+ to A&E+ suggesting that these participants were more comfortable at making approximations and estimations, instead of relying solely on data. However, making the estimations, and confidence in their estimation was not always beneficial to their strategy as demonstrated by participant PGHULL2. During problem 3 the participant was trying to calculate the volume of gas for each gas in the atmosphere and therefore how many atoms of each would be present based on the diameter of the atom. Participant PGHULL2's model collapsed under the assumption that only 20% of the atmosphere would contain mass and that the density of gas, and therefore the number of atoms in a given volume, would be the same throughout the atmosphere. Furthermore the participant assumed that CO_2, O_2 and N_2 were about the same (3A) and the participant did not evaluate their estimations through any other means, believing they must be correct because they had an answer. Coincidentally although the participants showed no lack of confidence in their estimations both PGHULL2 and PGHULL4 show signs of lacking confidence or became confused with the problem (CCP-). In the case of PGHULL2's transcript this had been observed when the answer calculated did not fit the template they had constructed in their mind, resulting in a heavy dependence on ALG+ approach in order to understand the problem better.

The third profile shown in the postgraduate students displayed by participant PGHULL5 showed retractions along IIN+ and A&E+ in favour of the more dominant approach of ALG+. The participant in this profile was showing a preference to making calculations as a method of verifying their chosen strategy, rather than asking for specific pieces of information or making approximations.

The overall profile for postgraduate participants (Figure 37) showed prominent approaches with IIN+, A&E+, ALG+ and IPF+, which was further supported by highlighted codes in Table 22. The profile observed in Figure 37 suggested that although postgraduate participants were exhibiting a larger variety of codes than the chemistry undergraduate participants the profile lacked the prominence in EVA+ observed in the chemistry academic participants. As such participants were not exhibiting expert like behaviour because both the Walsh *et. al.*[326] and Overton *et. al.*[316] definitions identify the characteristic as important to be an expert problem solver. Furthermore the traffic lighted success score of problem solving for postgraduate participants (Table 27) showed that they achieved fewer red solutions than the undergraduate chemistry participants (Table 29) but still did not achieve the same success as the academic participants. Postgraduate students therefore could be considered transitional towards becoming expert problem-solvers, lacking the experience in open-ended problem solving which academic and industrialist participants had used more frequently in their careers. However, caution should be advised with the data collected for the postgraduate students as the sample size was too small to draw any firm conclusions. The number of different profiles observed cannot be assumed to have captured all variations due to only five participants being involved. However, from this small group what can be said is that there was no one profile emerging from the individual participants, suggesting that they engaged with open-ended problems in variety of different ways.

6.9 Approaches Exhibited by Academic Group Participants

No literature has been identified that discusses the approaches used by groups when answering open-ended problems, despite the wealth of research looking at group dynamics and behaviours. This may be due to the difficulties of capturing think aloud data from a group interaction, and consequently, solutions rather than approaches are more easily documented.

This research encountered problems of quality with using think aloud data in a group, and as such that data for EMIXGP1 in Table 23 was considered

VOID because it would have been inappropriate to included. The static quality of the recording meant that not all information could be heard and therefore coded, resulting in a skewed understanding as to what approaches the group used. Furthermore, data was collected for undergraduate groups as seen in Table 7. However, the quality of the recording, as with the EMIXGP1 recording, was too poor for the data to be processed.

Identifying the information needed was a common emerging theme in the academic group participants, with Table 23 showing all but one group used IIN+ as a prominent approach in the initial stages of the problem solving activity. This was observed in participant group ECHEMGP1 who used identifying the information needed as an additional framing of the problem stage. However, other groups used identifying the information needed following a phase of framing the problem and after the development of a strategy. This was seen in group EPHYSGP2 who having decided to develop a strategy centred around the mass of the earth's atmosphere being linked to the displacement and density of mercury. The group clearly defined the information they needed in order to enact their chosen strategy. Table 23 *sh*owed group EPHYSGP1, who did not show prominence for identifying the information needed, however, as a group they were more focused about making the estimations and approximations individually rather than asking the interviewers or discussing the parameters as a group.

Academic group participants were much more confident at making approximations and estimations, also observed when individual academic participants worked through problems. Table 23 showed that approximations and estimations were a common approach in academic group participants and seemed to be as a result of two things. The confidence to make estimations and approximations within a group setting, and the reliance on expertise within the group. ECHEMGP1 as stated early relied on the experience of individuals to frame the problem, but also to create estimates. The participants in this group estimated the lifetime of the tyre to be 35,000 miles based on the estimate of a group member who stated they'd "*just recently changed my tyres.*" Another group, EPHYSGP2, also estimated the life of a tyre to be "*30,000 miles*", relying on the experience of individuals in the group. Because of the confidence of expertise within the group, the groups did not feel the need to ask for specific pieces of information from any of the interviewing team. This meant a synergy emerged between IIN+ and A&E+ where there was less reliance on 'fact finding' (IIN+) to develop a strategy.

All the academic groups focused heavily on making calculations and using equations. The types of calculations and equations used were the same as when academic participants solved open-ended problems as individuals. What was different about academic groups was the discussion about the calculations and the consultation between group members. Unlike the individual academic participants, the group participants had the opportunity to discuss what calculations needed to be made and as a group they could remember the required equations in better detail. This discussion was seen in ECHEMGP3 who stated

> "*so if we are doing it properly we will need to integrate it [density] from the surface up to zero…so we not that at about 10 miles up the atmosphere is about zero, so we can work that out.*"

In this example it was clear that the group was discussing the calculations they required to develop their strategy. Furthermore, although the interviewer expressed to the group they were able to provide those details, the group, for a time persisted in trying to calculate the density of the atmosphere. They eventually gave in and asked for the information. Although the group did not successfully calculate the density without additional supporting information, eventually the interviewer provided them with the data they required and they proceeded past this obstacle.

Although not all academic groups showed EVA+ as a highlighted code, it emerged as present in all of them. This evaluation manifested itself through multiple routes. One example was with EMIXGP2 where the participants engaged in the problem solving activity and developed a solution as a small group before passing the solution to another member of the group to see if the calculations were correct. This behaviour showed that the academic group recognised the limitations with their individual characteristics but could identify expertise within the group and relied on their ability as a single unit to develop a suitable answer. A further example of evaluation approaches was with UCHEMGP2 where the group split into two smaller groups and worked on the problem separately. With both smaller groups answering the problem from separate directions, they compared their answers to ascertain whether either group had a sensible solution. This development of two separate solutions ensured that if their solutions were wildly different then they could revisit the problem to determine where they went wrong. UCHEMGP2, although not working as a large team, worked collaboratively to evaluate using a ‘peer review’ process. Both the behaviours of EMIXGP2 and UCHEMGP2 were very different to the behaviours used by academic individuals, because when the academics were performing as individuals they could not rely on expertise outside the group.

The emergence of IPF+ was not surprising, since it has emerged in most other physical science participants. However what was surprising is the way in which IPF+ was used. Instead of framing the problem individually and creating a template or model through one individual, the group pooled their experiences together developing a more reliable framing process. What was more, although the framing resulted in much greater time being spent before committing to a strategy, the academic groups seldom returned to a framing process once they had embarked on their strategy. This emerged in ECHEMGP1, whereby the group asked for experiences of when people had changed their tyres, how far they had travelled on that set of tyres and whether anyone knew what the legal limit was for a set of tyres.

Almost all groups were able to develop a strategy , with some groups developing multiple strategies during the problem solving process (Table 23). Many of the strategies were the same as seen in the individual participants, however there was one strategy which had not previously been observed. This emerged in problem 2. This strategy involved participant group EPHYSGP2 who understood the relationship between density and height of mercury and the surface pressure of the atmosphere on the earth. This meant participants could calculate the mass. What was unclear from the recordings was whether this was a group driven initiative or whether one individual developed this strategy. The strategy was noticed when a participant within the group states “well consider a layer of mercury, that would be zero point seven six metres above the earth” to which many participants stated, “good point,” and “very good.” From that point the group developed a strategy focused on this relationship.

Academic groups rarely became distracted by the lack of information, with no groups showing it as a prominent approach (Table 23). However, one group showed more signs of becoming distracted by the lack of information than the other participant groups. Group ECHEMGP3 showed 7 examples of becoming distracted by the lack of information. This was seen by group members stating "*this about two angstroms and it is a close packed structure, and I guess, well you are talking about it as molecule. And it is a molecule. So is it in a sense like it is zigzagging slightly or is it one atoms worth [of the molecule]*" and "*are we just thinking of it as a simple structure, or is that just over complicating the issue?*" In both of these examples it can be seen that the members of the group were unsure about the data they required, or how to proceed with obtaining the information they required. In the first example the participant was engaging the group to discuss whether the question was correct to discuss an atoms amount or should it be a molecules amount of ware. The group discussed this for a while before one participant stated "I think it is just an average, I mean we know that it must be a molecule. But we can work out the average ware of a tyre for one atom."

All groups developed a logical and scientific approach to solving the open-ended problems (Table 23). Each group worked in a systematic way, and grounded their understanding and reasoning in scientific principles. This was shown by group EMIXGP2 who stated, "one revolution of the tyre should be sufficient… because it is a very small amount to remove." Another group, as stated previously, discussed the relationship between the density of mercury and the surface air pressure. They discussed the science behind the strategy, but also approached solving the problem by systematically identifying the information they needed.

Many academic group participants expressed confusion or lack of confidence with the problems. This normally materialised as lack of experience with problem 2 where some people were not sure how long a set of tyres lasted. For example UCHEMGP1 stated "*I don't why we would want it in picometers? I don't understand why?*" clearly showing that that individual struggled with contextualising the problem into their current template of understanding. Although that member of UCHEMGP1 struggled individually with their understanding, the group had sufficient expertise to help that individual develop their template so they were more confident with the situation. One unexpected example of a group becoming confused was again with ECHEMGP1 who when converting units struggled to change 8 mm into picometres, drawing one exasperated member to say "*how many chemists does it take to convert here.*"

The individual profiles for the expert groups showed mainly positive approaches, but they employed a broad variety of approaches whilst solving open-ended problems. Table 23 showed that academic group participants were all showing highlighted prominence in IPF+ and CCP-. However it is the wider variety of approaches highlighted that drew interest, in particular the use of A&E+ and EVA+ in some groups.

When the overall radar chart profile in Figure 39 was compared against the individual academic group participant radar charts, the positive code profiles most academic groups were closely similar in shape. The one group that was not similar to the other profiles in Figure 38 was the radar chart for EPHYSGP1, this was because that group displayed much less IIN+ than the other groups and therefore did not resemble the overall profile in Figure 39. It would have been inappropriate to identify the lowest codes exhibited in the overall profile for academic groups because many of the negatively coded approaches had 0% distribution towards those codes.

The recording for Group EMIXGP1 was unsuccessful and as such has been considered void for the purpose of this research. Attempts were made to digitally enhance the audio recording however the recording device had not recorded the details in the first place rather than the file becoming corrupt. A similar situation occurred for the chemistry undergraduate groups, wherein only one recording was suitable for coding and as result it had to be removed from the study. A different problem was encountered with the physics undergraduate group participants. The setup for this part of the experiment was in a large lecture theatre during a class problem solving activity. The problem solving activity was collaborative and students were encouraged to discuss with partners strategies and methods for solving the problems. However, this meant that the background noise was too high for the livescribe pens to identify the members of the groups who were being recorded. These complications have meant that five recordings have had to be removed from the study. More suitable methods of gathering group problem solving data needed to be investigated to ensure that these complications are not encountered again during a grounded theory emergent investigation.

6.10 Chemistry 'Experts' *vs* chemistry 'Novices': How do their approach profiles differ?

An objective of this study was to understand what approaches chemistry undergraduates in their first year of study, academic and industrialist participants used when solving open-ended problems. The analysis of the data in Table 14 showed that the approaches used by the undergraduate chemistry participants were very similar to each other; indicating that identifying the information needed (IIN+), using algorithms and making calculations (ALG+)

and identifying and framing the problem (IPF+) are prominent approaches used by chemistry undergraduate students when solving open-ended problems. The analysis presented in Table 14, Table 20 and Table 21 is supported by previous literature with individuals identifying and framing the problem as suggested by Polya[156] and Bodner[324]. What was not explained in these papers was whether identifying the information needed to answer the problem was grouped together with identifying the problem and framing what the problem was asking. Using an emergent analytical approach the data presented in Table 14, Table 20 and Table 21 clearly showed that IPF and IIN components are discretely separate. There are occasions when the chemistry undergraduate participants have used identifying the information needed as a method to frame the problem and develop a strategy when they are unsure how to proceed, as they searched for a piece of information they could anchor their strategy against. So although participants all identified the information needed, its implementation thereafter differed. In addition to identifying and framing the problem, Table 20 showed that academic participants engaged in more evaluation than the chemistry undergraduate participants (Table 14). Evaluation had been identified as an important skill in previous studies where it had been observed as the concluding approach of a problem-solving strategy.[148, 156, 324] In our study it appeared evaluation processes occurred toward the end of a solution, although as Table 38 showed some academic participants used evaluation during their solution in a reviewing process. The reviewing process was observed less frequently than the end of solution process and never occurred in undergraduate participants.

The data presented in Table 14, Table 20 and Table 21 also showed the prominence of using algorithms and making calculations associated with the questions in both chemistry undergraduates and expert participants. These open-ended problems could be answered through verbal reasoning as well as arithmetic reasoning, yet the focus of chemistry participants was towards an arithmetic processes. This is reflected in Table 14, Table 20 and Table 21 and where most participants showed ALG+ (using algorithms and making calculations) as a prominent code. Bodner[324] and Polya[156] did not identify the use of algorithms and making calculations as an important component of problem solving, presumably assuming its importance was implicit in solving chemistry problems and, as such, is an intrinsic tool in scientific problem solving. Although this approach was not identified as important for problem-solving in the Bodner and Polya studies, it was identified through a qualitative study by Overton *et. al.*[316] These authors used different terminology, stating that participants 'seek' an algorithmic approach. This was slightly different to the ALG+ code associated with our study which catalogued the events and approaches through the 'use' of algorithms and calculations. Unsurprisingly, a large number of participants utilised arithmetic processes, as their previous experience in problem solving have focussed around using algorithms, equations and calculations to solve most problems.[344, 345] When participants encountered an unfamiliar experience they tried to imprint a more familiar process, such as transforming an open-ended problem into an algorithmically structured problem through framing the problem and applying equations. This was further reflected by Nakhleh who asked "*Are our students conceptual thinkers or algorithmic thinkers?*"[200] Data presented by Cracoline *et. al.* suggested that a significant fraction of students have under developed reasoning skills forcing students to approach conceptual problems through algorithmic processes.[361] This maybe the same for open-ended problems, whereby participants were unable to cope without an algorithmic approach.

The analysis of the data from Table 24 and Table 26 and Figure 18, Figure 34 and Figure 36 highlighted the most interesting correlations between different groups, presenting the overall profiles of the three groups. This has identified that the primary approaches used by chemistry undergraduate, academic and industrialist participants were very similar. However, when the secondary prominent codes were identified it emerged that the chemistry academics looked very different to the chemistry undergraduate and industrialists. The profile for academic participants showed a much great number of secondary approaches than compared with the chemistry undergraduate and chemistry industrialist participants. As previously stated "*the means by which an individual uses previously acquired knowledge, skills and understanding to satisfy the demands of an unfamiliar situation*"[146] resulted in greater success at solving the problem. Camacho and Good[346] identified behaviours required to be a successful problem solver, including approaches such as identifying and framing the problem, evaluation and logical and scientific approach and developing a strategy. The approaches identified in the paper by Camacho and Good are similar to the approaches identified during our study.[346] The data in Table 20 clearly showed that academic participants exhibited a greater number of similar characteristics to each other when compared to undergraduate chemistry participants using the Camacho and Good definitions.

Overton *et. al.* suggested three different profiles of problem solvers in open-ended problem solving. These were novice, expert and transitional.[316] The definitions of each of those groups were:

Novice: Participants who adopted negative and unhelpful approaches, lacking scientific strategy and unable to define the problem, little to no evaluation occurred. Furthermore they were unable to detach themselves from the context of the problem and seek an arithmetic approach. 'No clear approach.' No clear approach was a term used by Walsh et. al.[340] who identified that participants with no clear approach analysed the situation based on the given variables, proceeded by trying to use the variables in a random way, referred to variables as terms and conducted no evaluation.

Transitional: Participants who employ a wide range of approaches depending on the problem, dependent on whether they could identify the problem and contextualise the data they needed. These participants evaluated their solutions, but still usually sought an algorithmic approach.

Expert: Participants who adopt predominantly positive approaches, understanding the problem and employing a logical scientific method. Participants in this group can handle the lack of data and evaluate their solutions.

Participants in our study did not stick strictly to the Overton *et. al.* definitions, as all participants used an arithmetic approach (ALG+) and all participants were able to identify and frame the problem (IPF+).[316] However, what should be noted is the difference in the use of evaluation. The undergraduate chemistry participants rarely used evaluation in their approach, and where it occurred was superficial, surface evaluation. The undergraduate chemistry participants also became confused with the problem and lacked the confidence in their ability. Industrial participants engaged in much more meaningful evaluation than their undergraduate counterparts, which emerged in Table 24 as a secondary code. Academic participants also engage in evaluation, and to a greater extent than both the industrialist and undergraduate groups. The academic use of evaluation emerged as a secondary code in Table 26 in addition to three other secondary codes. As such, the academic group could be identified as experts under the definition by Overton *et. al.*. because they were able to engage in a wider variety of positive approaches and achieved greater success in the process.[316] The chemistry undergraduate participants could be categorised as novices due to their lack of meaningful evaluation, resulting in low success rate as reflected in Table 27. This in-turn meant that under the Overton and Potter paradigm, industrialists are transitional, because although they achieved greater success than the chemistry undergraduate participants because of the approaches and evaluation of their strategies and solution. Industrialist participants still focused on developing an arithmetic procedure and became confused with the problem and their ability, even after clearly defining the problem. This supports the results of the traffic light data as seen in Table 29.

The traffic lighted solutions in Table 29 showed the quality of participants' solutions based on their written scripts. The percentage distribution for the green solutions showed that the chemistry undergraduate solutions had a lower percentage of success (20%) than the academics (37%) and industrialists (39%), with the academics achieving the highest percentage of green solutions. Undergraduate chemistry participants further showed most unsuccessful solutions (37%) followed by industrialists (28%) with the academics showing the least percentage for unsuccessful solutions (17%). Although a pattern was beginning to emerge from this data, the numerical scores provided another way to evaluate relative success.

6.11 Physical Sciences *vs*. Other Disciplines

The data presented has identified some interesting patterns in how different disciplines exhibited approaches when answering open-ended problems. Table 14, Table 15 and Table 18 showed that physical science undergraduates were very similar in their approaches to answering open-ended problems both as individuals and as an overall discipline, whereas the life science disciplines were more diverse with their approaches. This can be seen more clearly in Table 24 and Table 25 which demonstrated the secondary coding approach to the overall discipline profiles for each discipline. Physical science participants showed predominantly positive primary and secondary codes. When these were combined, although there were differences between which codes were primary and secondary for physical sciences, they resulted in almost identical prominence. The life science participants showed predominantly a mixture of positive and negative approaches which suggests that they used less successful approaches when solving open-ended problems. This is further supported by the traffic light data in Table 29, which showed that participants in the life science scored a higher percentage of red solutions, with sports rehabilitation at 67%. This is a marked difference when compared against the physical sciences where the highest percentage red traffic light scored was in chemistry participants at 39%. When the data was compared against the green traffic lighted solutions in Table 29 it was clear to see that once again that the life sciences were lacking good solutions when solving open-ended problems. This was seen with the highest scoring discipline for green solutions in the life sciences being only 10% (pharmacy) whereas the lowest for the physical sciences was 20% (chemistry). The data comparing disciplines indicates some agreement with Overton *et. al.* who stated that participants that used more positive approaches were more successful at solving open-ended problems. Although this was not as easily observed in the individual profiles, it was clear from the discipline profiles, that those disciplines that used more positive approaches were more successful at solving open-ended problems, with a hierarchy emerging between the physical sciences and the life sciences. The hierarchy was that physics participants were more successful at solving open-ended problems, followed by interdisciplinary science participants, then chemistry participants, followed by pharmacy and sports rehabilitation and then finally by psychology participants who scored the lowest average traffic light score.

6.12 M-Capacity and Field Independence in the science population.

The psychometric data provided from the different science disciplines was collated and represented in Figure 40 and Figure 43. Figure 40 and showed that participants in the science disciplines show a tendency to score high on the FIT test using the FIT-1 marking scheme. This was not surprising, because the FIT test is taken to be normally distributed from the general population, suggesting here that the population in this study was not normally distributed with respect to the general population. Participants in this study have had to achieve academically in order to attend university. Figure 40 however was not able to identify the distribution between disciplines as insufficient data had been collected for sports rehabilitation and interdisciplinary science disciplines (assessed through the Figural Intersection Test). Individuals with a high M-Capacity had a high-attentional energy available for a particular task.[89] Figure 40 would suggest that most participants tested using the FIT had a high availability of attentional energy, and should therefore not be affected by a cognitive load of the problem below their functional M-Capacity.[211] The FIT scores for all the disciplines were correlated against the percentage distribution of each code where a participant had also been interviewed. This was done in order to determine whether a link existed between specific codes and FIT scores. Table 41 presented the data for this correlation, and showed only one code was determined to be significant. The only test that showed significance was that for between FIT-1 scores and IIN-% (n= 56, r_s= -0.340, p=0.010), with values that demonstrated a low negative correlation. The data presented in Figure 41 clearly showed a threshold effect emerging in the upper left hand quadrant. This suggested that participants that have a low M-capacity did not not identify the information needed. However, participants that had a high M-capacity still did not not identify the information needed. What is of interest was the number of participants that scored a high M-capacity and showed no amounts of not identifying the information needed (shown in figure 41 with darker outlines from other data points).

When analysing the data presented in Figure 41, the graph of GEFT scores showed a dual peak emerging, whereby the number of participants who scored median test values dipped. What was interesting was that the mean value centres around just above the dip, suggesting the peaks either side of the dip were fairly evenly proportioned, a summation supported further with a skewness of -0.028. Once again the analysis of the data for each individual discipline would have been inappropriate due to the low number of participants for some disciplines. The GEFT scores for all disciplines were correlated using Pearson's correlation against the percentage distribution of each code where a participant had also participated in the 1-to-1 problem solving activities. This was done in order to determine whether a link existed between specific codes and GEFT scores. Table 42 presented the data for this correlation, and as the data showed six tests were significant. The tests which showed significance were IIN+%, LSA+%, IIN-%, ALG-%, DAS-% and LSA-%.

A variety of factors needed to be considered when discussing the relationship between the quantitative psychometric data and the approach identify the information needed (IIN). Despite the significance of the correlation observed between FIT score and IIN-%, Figure 41 showed a correlation that was low. However, as discussed earlier in the results section, greater importance was assigned to the quartering of the plot area. Figure 41 showed a clear void area towards the upper left of the plot area which suggested that participants who scored low on the FIT psychometric had low frequencies of not identify the information needed. Furthermore, participants that scored high on the FIT showed a varied percentage distribution for IIN-%. This suggested that a high FIT score was not a good indication of whether a participant would not identify the information needed.

Figure 44 presented the scatter data for GEFT score against the IIN+% (n= 62, r_s= 0.406, p=0.001). Despite the medium positive correlation, it was difficult to determine the trend from observing. However, there appears to be a trend whereby participants who scored lower on the GEFT identified the information needed less, and a higher score on the GEFT could result in more instances of identifying the information needed. Using this filter, one can observe an elliptical pattern in the data, which would visually represent the underlying Pearson's correlation.

Figure 45 represented the data for the GEFT score against the LSA+% (n= 66, r_s= 0.407, p=0.001). The data suggested that there was a medium positive correlation. However, this trend was difficult to visually see when looking at Figure 45. There appeared to be an elliptical cluster (from lower left to upper right hand areas of the chart) emerging in the middle of the chart area, suggesting that participants with a higher score on the GEFT test were more able to develop a logical strategy than participants with a low GEFT score. However, participants that showed no signs of developing a logical and scientific approach (LSA+% = 0), can be seen to score low, medium or high on the GEFT test. This suggested that field independence was not sufficient to determine the use of a logical and scientific approach.

Figure 49 represented the data for the negative medium correlation in the GEFT score against the LSA-% (n= 62, r_s= -0.347, p=0.006). The Pearson's correlation was again difficult to see in Figure 49. The value for the correlation matched nicely with the pattern against those for GEFT vs LSA+% as discussed earlier. What was observed was the reoccurring indication of the threshold effect. Figure 49 clearly showed a void in the upper right of the chart area. The void area represented the lack of participants who scored high on the GEFT and lacked a logical and scientific approach. Of further interest was the spread of GEFT scores in participants that showed 0% for lacking a logical and scientific approach. Figure 49 clearly showed that individuals with a high dis-embedding ability were able to predict a lack of a logical and scientific approach, although a low dis-embedding ability was not a strong indication of whether individuals used a none logical and scientific approach.

Figure 46 represented the data for the GEFT score against the IIN-% code (n= 62, r_s= -0.396, p=0.001). However, the Pearson's correlation was weak. When the chart area was quartered a void emerged in the upper right quarter. This suggested that participants that scored high on the GEFT were unlikely to be unable to identify the information needed to solve the problem. This was encouraging as participants with a high GEFT score should have the ability to dis-embed the required information to solve the problem. However, a high GEFT score was a predictor of low levels of not identifying the information needed. As Figure 46 showed, many participants showed 0% for IIN-%, despite a wide variety of scores on the GEFT. This meant that the GEFT score could indicate the chance a participant would use not identify the information needed infrequently.

Figure 47 represented the data for the GEFT score against the ALG-% (n= 62, r_s= -0.262, p=0.039) and showed a low negative correlation, whereby participants that scored low on the GEFT showed high levels of not using algorithms and equations (ALG-). Furthermore, Figure 47 showed that participants who scored high on the GEFT were unlikely to use equations and making calculations. Once the chart area in Figure 47 was quartered, a void area emerged in the upper right. This void area appeared to be identifying that participants that scored high on the GEFT used low incidences of not making calculations or estimations. This meant that participants that showed field independent behaviour were able to dis-embed information (a high GEFT score), meaning they did not use high levels of not using calculations and equations. The participants that showed 0% for ALG-% scored a mixture of high, low and medium on the GEFT. This meant that GEFT results were not indicative of participants not using calculations, but rather field independent individuals did not use high amounts of not using calculations and equations when solving open-ended problems.

Figure 48 represented the data for the GEFT score against the DAS-% (n= 62, r_s= -0.274, p=0.031). The Pearson's correlation suggested a weak negative correlation, which was difficult to observe in Figure 48. Once again, what was of interest was the upper right quadrant of the chart, which identified that few people who scored high on the GEFT were unable to develop a strategy (DAS-). This may be because participants who scored high on the GEFT were field independent and this allowed them to dis-embed the information in the problem.

Figure 42 showed the correlation between FIT score and traffic light score. The data was subjected to Pearson's correlation, and there was no significance between FIT score and traffic light combined score. This was interesting because Overton and Potter[219] identified a threshold effect between success at solving problems and M-capacity. Figure 42 did not reflect this clearly and this may be as a result of multiple disciplines being represented in the data. Overton and Potter report only using 1st and 2nd year chemistry students, whereas our study has included participants from different disciplines in their first year of study. Although the correlation was not significant, Figure 42 displayed a threshold effect for the FIT, whereby participants that scored low on the FIT test did not score high success at solving open-ended problems. Pascual-Leone, said that participants that scored high on the FIT had a high mental attentional energy available for problem solving, however in our study it is not clear as many participants scored low success despite having high M-capacity.[89] This meant that FIT test can be used to determine whether a participant will not be able to achieve high success at solving open-ended problems based solely on the score they achieved on the FIT test.

Figure 50 showed the comparison between GEFT score and the combined traffic light score . The scatter showed a significant correlation although the relationship was not definitive to visually see (n= 79, r_s= 0.359, p=

0.001). Furthermore, there was a less visual threshold effect than could be seen in the comparison between FIT score and combined traffic light data. An elliptical shaped distribution of the data was observed, however, it was difficult to identify. The elliptical shape emerging was that participants that scored very high on the GEFT test (15+) did not score very low on the combined traffic light data scores. In addition, participants that scored very low on the GEFT test (less than 7) were unlikely to score high on the combined traffic light data score. Despite these trends emerging, the ellipse of data points is very broad, whereby participants who scored 15 or less on the GEFT score could score a variety low to medium on the combined traffic light scores. This suggested that participants' success at solving open-ended problems was not as clearly defined through field independence psychometric parameters as algorithmic questions. Furthermore, an additional complication with this data was that it is multi-disciplinary and, as identified during the qualitative component of our study, participants in the physical sciences approached open-ended problems in very different ways to participants in the life sciences. A greater amount of data is required from life science disciplines to determine whether these participants may be altered/ shifted what was being observed in the data of previous studies, or rather the way life science participants approached answering the problems effected their success based on psychometric data.

Figure 51 showed the comparison between the FIT and GEFT scores in all participants (n= 172, r_s= 0.374, p=0.000). The scatter graph clearly showed that participants achieved a wide variety of scores on the GEFT, whilst still maintaining a high score on the FIT. This was seen by a contrasting pair of participants, whereby one participant scored 5 and another scored 19 on the GEFT, however both achieved a score of 29 for the FIT. A further example of this was seen in two other participants who scored 3 and 17 on the GEFT respectively, but both scored 5 on the FIT. When the data was subjected to a Pearson's correlation test, a positive low correlation was observed (n= 172, r_s= 0.374, p=0.000). Figure 51 demonstrated that some participants, despite having the cognitive load capacity to process the information still lacked the ability to dis-embed the information, in essence the difference between field independent and field non-independent individuals. This pattern of behaviour had been observed through the threshold effects in the previous comparisons between GEFT scores and individual approaches. However, based on the current data it was difficult to state whether the GEFT was responsible for the diversity in performance, because Figure 50 showed no threshold or correlation between GEFT and combined traffic light scores. The psychometric data presented here suggested that the cognitive and psychometric complexity in open-ended problem solving is far greater than can be determined by the current data.

7 Conclusions

The final aim of the research was to understand the approaches used by science students, chemistry academics and industrialist when solving open-ended problems and how these might be effected by cognitive factors.

The research reported in this thesis has identified a number of findings which enhance our understanding of how science students and experienced chemists solve open-ended problems and that may have impact on future teaching and learning which relates to problem solving.

The study identified that across multiple disciplines there are a finite number of approaches observed and used to solve open-ended problems. The eight approaches used by individuals when solving open-ended problems were:

- Identifying the information needed.
- Making approximations and estimations.
- Algorithms (making calculations and using equations).
- Evaluation.
- Identifying and framing the problem.
- Developing a strategy.
- Not distracted by detailed context of the problem.
- Using a logical and scientific approach.

The research also identified that participants sometimes became confused with the problem and lacked confidence in their ability. Although this was identified as not strictly an approach and more a behaviour, the level to which it occurred required it to still be considered.

The research clearly identified a difference in the individual discipline profiles of chemistry undergraduate students, chemistry industrialists and chemistry academics. Chemistry undergraduate students conformed to a very specific profile when they answered open-ended problems. Chemistry undergraduate students focused their approaches towards identifying the information needed, making calculations and using equations and identify and framing the problem. Industrialist participants had a profile which is similar to undergraduate chemistry participants, focused towards identifying the information needed, using algorithms and making calculations and identifying and framing the problem. The main difference between industrial participants and undergraduate chemistry participants was that industrialists used more evaluation. The academic participants used a broader range of approaches when compared to both the undergraduate chemistry participants and industrialist participants, and showed further use of approximations and estimations, evaluation of solutions and answers, developing a strategy, not becoming distracted by information and developing a logical and scientific approach. Academic participants used more evaluation than both the other groups. Further differences emerged between these groups with respect to the success at solving open ended problems. Academic participants were the most successful, followed by industrialists and then the chemistry undergraduate participants. The combination of approaches and success of academic participants classified them as expert problem solvers, with industrialists considered transitional problem solvers and chemistry undergraduate students remained as novices. These classifications clearly demonstrate a hierarchy of expertise within the chemistry community with respect to success at solving open-ended problems and the quality of the approaches used. The approach which appeared to make the greatest difference to success in these disciplines was the use of evaluation. Chemistry academic participants used a greater amount of evaluation when solving open-ended problems than chemistry industrialists and chemistry undergraduate students. As such, the greater use of evaluation contributed to their greater success. This means that to improve expertise at solving open-ended problems in undergraduate chemistry students a curriculum that focuses and nurtures evaluation and self-reflection could be beneficial to create better problem solvers.

The data presented has identified some interesting patterns in how different disciplines solved open-ended problems. Undergraduate physical science (chemistry, physics and interdisciplinary science) participants were similar in their approaches to solving open-ended problems both as individuals and as overall disciplines. This similarity was observed despite changes in the question order and provision of alternative questions. Furthermore, physical science undergraduates used predominantly what have been defined as positive approaches when tackling the problems. When the physical sciences participants are separated into individual disciplines, it is difficult to identify significant differences in the approaches used. However, it can be said that there was a slight increase in confidence at solving open-ended problems in the interdisciplinary science participants than the other physical sciences disciplines. This may be due to their curriculum being entirely delivered through problem-based learning and so exposure to unfamiliar and open-ended problems had less impact on their confidence. Chemistry undergraduate participants primarily identified the information needed, used equations and calculations and identified and framed the problem. They made approximations and estimations and developed a strategy to a lesser extent. Physics participants identified the information needed and used equations and calculations. They made approximations and estimations and identified and framed the problem to a lesser extent. Interdisciplinary science participants identified the information needed and only made approximations and estimations, used equations calculations, and identified and framing the problems to a lesser extent. Although there are differences between which approaches were prominent and less prominent for these three disciplines they all covered the same positive approaches.

Whilst most physical science participants approached solving open-ended problems in a similar way, the degree of success of the different disciplines was quite varied. Physics participants were more successful than interdisciplinary science participants and chemistry participants were the least successful participants of the physical sciences. This clearly showed that the quality of the approach, rather than just using a particular approach, results in different success. A particular approach which impacted on the success in the physical sciences was the use of equations and making calculations. This could be because physics undergraduate students are more accustomed to modelling and using mathematical principles than chemistry and interdisciplinary science because they all had A-level maths or equivalent. Intervention workshops that encourage the use of modelling and enhancing mathematical skills could result in increased success at solving open-ended problems in chemistry and interdisciplinary science participants and could be developed and integrated into existing degree programs.

Life science disciplines (sports rehabilitation, psychology and pharmacy participants) were more varied with their use of approaches which means that it is less easy to rationalise their success from the approaches they used. This was demonstrated further through the secondary coding approach of the overall discipline profiles for all the disciplines. None of the life science discipline profiles looked similar to each other or to the physical sciences profiles, indicating that there was a lack of consistency in approach when compared against the physical sciences. The life science profiles showed a mixture of positive and negative approaches which is different from the physical science disciplines. When the life science disciplines are separated the varied profiles of individual participants remains, demonstrating that it is difficult to identify the discipline of the individual from their individual profile. Sports rehabilitation students identified the information needed, made approximations and estimations, identified and framed the problem, and lacked a logical and scientific approach. However, they did not make approximations and estimations, used no equations and didn't make calculations, and lacked evaluation. Psychology participants identified the information needed, made approximations and estimations, identified and framed the problem, lacked calculations and didn't use equations, failed to evaluate their solutions and answers, and lacked a logical scientific approach. Psychology participants developed a strategy to some extent and were not distracted by the lack of information. Pharmacy participants identified the information needed, and identified and framed the problem, used equations and made calculations but did not make approximations and estimations, lacked evaluation, and became distracted by the lack of information. As can be clearly seen the three disciplines in the life sciences used many more negative approaches than their counterparts in the physical sciences. This wider variety of approaches to solving open-ended problems observed in the life science disciplines may make it more difficult to develop specific intervention strategies to increase the success of participants at solving open-ended problems. One suggestion would be to encourage participants in life science disciplines to use more positive approaches and, in particular, those used by chemistry academic problem solvers to increase their success at solving open-ended problems. This would mean encouraging life science participants to use more evaluation and become more reflective when solving open-ended problems. A further key difference was the lack of using equations and making calculations despite the problems being suitable to be answered through verbal or numerical reasoning. This suggests that an understanding of or confidence with maths is required to be successful at answering these types open-ended problems.

The research showed a hierarchy for success at solving open-ended problems with the physical sciences as discussed previously followed by pharmacy and sports rehabilitation, and finally psychology. This hierarchy demonstrated a clear separation for success between the physical science participants and the life science participants. As previously stated, the reasons for the emerging hierarchy of success at solving open-ended problems could be reflecting the mathematical ability of participants, including their comfort and understanding of numerical principles. These finding could have implications for teaching, in particular psychology and pharmacy which are disciplines known to require mathematical ability, yet achieved low success at solving open-ended problems. This study cannot determine whether increasing mathematical ability in life science disciplines would result in greater success, however, it demonstrates the requirement for an intervention study to determine whether embedded mathematics training results in greater success at solving open-ended problems. Furthermore, this hierarchy could have implications for graduate recruitment where a recruiter who is aware of the differences in success at problem solving may be more inclined to recruit a graduate from physics or chemistry than pharmacy or sports rehabilitation.

The approaches used by a group of academic participants were also investigated. What is clear from the data is that working as a group increased the success of solving open-ended problems compared to working as an individual. This suggested that even academics who scored highly as individuals can gain a benefit from working in a collaborative environment. These findings suggest that the use of group work would lead greater success at solving open-ended problems in all ability groups, as enhancement has been demonstrated even in high achieving groups.

Our student population had a high M-capacity, meaning the undergraduate population should not be as susceptible to cognitive overload as readily as the general population. Our undergraduate population showed a mixture of field independence and none field independent participants. Attempts to link these cognitive factors with specific approaches used by participants when solving open-ended problems were not very successful. Some threshold effects were observed between negative approaches and M-capacity and field independence. These threshold effects were observed between the following approaches:

- Not identifying the information needed *vs* FIT score: participants that scored low on the FIT test had low frequencies of not identifying the information needed.
- Not identifying the information needed *vs* GEFT score: participants that scored high on the GEFT test had low frequencies of not identify the information needed.

- Not using equations and making calculations *vs* GEFT score: participants that have a high GEFT score had low frequency of not using equations and making calculations.
- Not developing a strategy *vs* GEFT score: participants with a high GEFT score had low frequency of not developing a strategy.
- Not using a logical scientific approach vs GEFT score: participants that scored a high GEFT score had low frequency of not using a logical and scientific approach.

This means that people who are field independent used fewer negative approaches or didn't show a particular approach when solving open-ended problems. The image is less clear with respect to M-capacity because the only correlation identified was a low correlation. .

A further threshold effect emerged when comparing cognitive tests against the quality of solutions. Participants with a low M-capacity were unlikely to achieve high success when solving open-ended problems. The relationship between field independence and quality of solutions was less clear because some participants that scored very low on the GEFT test were still able to score high on the traffic light data. This suggests that despite field independence being an indicator for the types of approaches used when solving open-ended problems, it is not sufficient to determine success at solving problems.

There are some limitations associated with this research. These include a small sample sizes of some disciplines for the cognitive tests and the small sample of sports rehabilitation students for the qualitative analysis. Furthermore, the research does not account for the differences in the effect of gender, prior experience and academic achievement, which could possibly have some influencing factor in the cognitive tests and the manner in which approaches emerged. However, despite these limitations the findings do have implications for undergraduate education and teaching open-ended problem solving. It was clear that success in solving open-ended problems is aided by the use of evaluation. Undergraduates should be encouraged to evaluate throughout the problem solving process, not just for the final solution, developing problem solvers with a more reflective mind set. In addition, expert problem solvers utilised a wider range of approaches. This expert behaviour is exhibited by chemistry academics and it could be the extensive experience of research that inculcates such behaviours. However, despite certain characteristics being present, their presence is not sufficient to develop or identify expertise at solving open-ended problems. Even participants who were unsuccessful at solving open-ended problems still demonstrated most of these characteristics. Therefore, it is not only important to encourage students to use certain approaches when solving open-ended problems, but also develop their experiences with solving open-ended problems to increase the quality of their approaches. The main approach that resulted in a difference was the use of evaluation, specifically identified through the chemistry academic participants, this means undergraduate students need to be encouraged to adopt greater reflective and evaluative practices to develop expertise to increase the chances of success at solving open-ended problems. In order to enhance undergraduates' problem solving abilities and move them towards expert-like behaviour a curriculum with a bias towards undergraduate research and problem solving activities could be beneficial.

8 Further Work

To further understand how approaches used in solving open-ended problems differ across the STEM disciplines the study could be extended to include participants from the biological sciences. This would help to establish how students studying biological sciences solve open-ended problems and whether the approaches used are similar to the physical science approaches or demonstrate a unique profile of their own.

Further data should be collected from participants studying sports rehabilitation and psychology to increase the reliability of the data for the discipline profiles. Currently, because of the small sample sizes, the data from these two groups can only be considered as indicative and does require additional data to corroborate the profiles developed within this thesis. With a more accurate profile of approaches used by sports rehabilitation and psychology students, intervention would be more successful to develop problem solving skills in these undergraduate students.

Data relating to academic group approaches for solving open-ended problems has already been discussed. However, the quality of the audio data collected for chemistry and physics undergraduate groups was poor and unusable. Interactions between group behaviour, approaches and success when solving open-ended problems should be investigated to ascertain whether participants in groups behave differently from individuals. Preliminary results have been demonstrated within this thesis for academic group approaches and enhanced success. Undergraduate student groups would not only provide data for how successful student groups are at solving open-ended problems but would potentially reinforce the available evidence on the beneficial nature of group work activity within undergraduate degree curricula.

The data relating to the psychometric tests (FIT and GEFT) should be expanded for sports rehabilitation and psychology, in order to increase the validity by ensuring a larger sample size. The data for the Figural Intersection Test (FIT) and Group Embedded Figures Test (GEFT) tests should be processed to establish if trends exist within these specific discipline populations and how the psychometric profiles differ between disciplines. This would require additional testing of the FIT and GEFT being administered to specific science discipline cohorts.

In order to investigate the impacts of fixed and mobile learners large sample sizes of participants who have completed the GEFT and FIT tests are required. The phenomena of fixed/mobile learners has been demonstrated in algorithmic problems but not for open-ended problems. This study was unable to recruit sufficient numbers of participants to investigate this phenomenon, but the impacts on success and approaches when solving open-ended problems by fixed/mobile learners maybe important.

This project has identified that identifying the problem and framing the problem are important when tackling open ended problems. What isn’t clearly understood is the complexity of the framing process. Further work needs to be conducted looking at the complexity and significance of the ‘models’ students build when answering open-ended problems and how this framing process might impact upon success.

Finally, this study has established that undergraduates from different academic disciplines employ different profiles of approaches to solving open-ended problems. What isn't known is whether these different approaches are a product of the students' training in a particular discipline, or whether students with a particular approach are attracted to a particular discipline. This would be a fascinating area of research and would require a large scale longitudinal study.

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Appendix 1: Hull University Ethics Approval Form

Appendix 2: Leicester University Ethics Form

Appendix 3: The Figural Intersection Test

Appendix 4 Group Embedded Figures Test