The impact on students’ self-efficacy and attainment of the explicit teaching of cognitive and metacognitive problem solving strategies in post -16 physics. The case for a GCE A-level physics course in an inner London Academy

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Ronald Mazorodze

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Dedication

This dissertation is dedicated to my late grandparents who adopted me, Paradza and Fungisayi. For the love and care you provided throughout the good and difficult times of my young life, and for laying that solid life foundation of my life. For that great lesson, to ever work hard despite limited resources. Not to rest because the day has rested!

Abstract

Problem solving plays a pivotal role in the physics curriculum at all levels, as a summative assessment tool or a pedagogic barometer to gauge transfer of acquired physics knowledge and skills. However, evidence shows that students' performance in problem solving remains limited to basic routine problems, with evidence of poor performance in solving problems that go beyond basic equation retrieval and substitution. Research into physics problem solving, with very little literature existent for the UK, has advocated for explicit teaching of problem-solving strategies but with little impact of these studies on the actual learning-teaching process of physics.

In heeding the call by most researchers to extend research on physics problem to real classrooms situations, an action research methodology, consisting of two cycles, was adopted. This action research study attempted to bridge the `research-practical divide´ by explicitly teaching physics problem-solving strategies through collaborative group problem-solving sessions embedded within the curriculum.

The target group was a GCE-A level cohort in the AS course, the only course cohort at this inner London academy. The objective was to trigger the generative mechanisms identified within the information processing, sociocultural theory and social cognitive theories. These mechanisms were viewed as possessing causal powers to enable an improvement in physics problem-solving competence. Data were collected using external assessments and video recordings of individual and collaborative group problem-solving sessions.

The data analysis revealed a general positive shift in the students' problem-solving patterns, both at group and individual level. All four students demonstrated a deliberate, well-planned deployment of the taught strategies. The marked positive shifts in collaborative competences, cognitive competences, metacognitive processing and increased self-efficacy are positively correlated with attainment in problem solving in physics. However, this shift proved to be due to different mechanisms triggered in the different students.

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EdD Reflective Statement

My enrolling into the EdD programme is the continuation of a personal journey which started way back in Africa in 1978. At the age of seven and at the height of the war of independence in my country of origin, Zimbabwe, I was enrolled at the nearest primary school, five miles away. The journey to school barefoot and sometimes on an empty stomach, followed by many hours of learning sitting on crammed desks with very few resources solidified my resolve to study as much as my intellectual ability could allow. Since then I have witnessed two of the many primary school friends in rural Africa attain doctorates with world-renowned institutions. Later, I would receive two government scholarships to study in Cuba for my first degree and postgraduate study as well. Upon completion of my postgraduate studies, I moved to the UK.

Teaching in the UK presented a different professional context which demanded a shift in my pedagogical and professional approach to teaching physics and other sciences. Upon completing five years in the UK and attaining permanent residence, I took up my quest to further my education. My initial interest for the EdD studies was on how girls learn physics. At that time I was working in an independent all-girls school. However, during the course of the first two years in the EdD programme, as well as through studying and changing places of work and working with different communities, my research interest shifted considerably as I shall discuss later.

My first taught course, FOP, culminated with an assignment: *The professional implications of the National Curriculum's GCSE 21st Century Science for Physics Teachers in England. A teacher's perspective.* In this assignment I considered issues around the impact of central government politics on how state-funded schools are expected to meet certain targets with little or no consideration of their contexts and explored how this discourse of perfomativity leads to fabrication of data. The macropolitics of perfomativity from the central government drive the micro-politics of a school as the school leadership struggle to fulfil certain targets through a top-down approach which leaves the teacher with no autonomy.

This assignment was an eye opener in terms of understanding my profession as an overseas-trained teacher within a new context. This was my largest piece of academic writing in English after studying all my degree courses in Spanish.

The second module, Methods of Enquiry 1, introduced me to the real world of social research. Most notable were the ideas of paradigms and theoretical perspectives. My assignment title was *How socio-cultural factors impact on the attitudes of girls towards GCSE physics and the subsequent take-up of post-16 physics.* The choice of the area for this study was influenced by research done by Ponchaud *et al*. (2008) on girls in the physics classroom and my initial focus on girls and physics learning. Having changed jobs to teaching in a multicultural setting within a predominantly asylum seeker community with about 40% of the pupils being Muslims, the low representation of girls in physics classes at advanced level echoed the findings of this study. From the data collected from the girls using questionnaires, followed by interviews, socio-cultural factors within the classroom setting were identified as some of the causes leading to the low uptake of physics by girls for post-16 study. This study highlighted the importance of cultural contexts when planning activities within a co-educational setting. As an example from this study, a common classroom behaviour management technique is the alternating sitting of boys with girls. However, it emerged in my interviews that, given the opportunity, girls prefer to sit in female-friendship groups and do most practical work with their friends. This arrangement, they argued, eliminates the boys' random approach to practical work and affords them an opportunity of physically doing the practical activity. The alternate boy-girl seating plan, though adopted as a school policy, didn't provide a comfortable learning environment for some of the girls, it emerged.

The challenge for me as a practitioner was to adopt learning approaches that took into account these findings from my study. A major obstacle to this assignment was the scarcity of literature that focussed on science learning within such a setting, particularly ones that employed a socio-cultural theory on science learning.

For my specialist course, the `Leadership and Learning´ assignment, I chose *Leading the successful learning of secondary physics to ethnic minority groups in urban schools* as my topic. In this assignment I argued the case for an urban curriculum in physics, and other sciences, tailored for deep learning of physics, but resonating with the learners' socio-cultural contexts. I also noted that little research had been undertaken on how the curriculum and pedagogy of science in urban England needs to change to cater for the ever-changing demographic landscape. For my school, its multicultural composition and the largely asylum seeker background of the learners meant a tangible obstacle in accessing the scientific language used in physics, and other subjects.

In this assignment I also argued for a systems approach to science learning as opposed to the existing approach of different departments functioning independently rather than organs of one organism in achieving goals. A case in point was the fierce competition and lack of cooperation between the science and mathematics departments in my school and inadequate cooperation with the EAL department. Reviewed literature showed that systems thinking can enable us to work with patterns, relationships and subtle interconnections of the learning organisation as a living system. Successful learning of physics, and any other subject, in a city setting hinges on awareness of the myriad of factors that are at play in an urban learner's life.

A `school as a learning organisation´ approach would help in understanding the interactions between the different factors that form the complex urban environment and the influence of these on learners' attainment. This assignment triggered a shift in me, causing me to focus on those processes and mechanisms at play within the learning environment that i could influence as a practitioner. For my MOE-2 assignment I wrote on *Measuring students' motivation and learning approaches towards GCSE physics in a London urban multicultural comprehensive school*.

This study was aimed at determining different levels of motivation in physics for a GCSE cohort within my school of practice. With this assignment, the real challenges of doing research were highlighted, from formulating the research questions to data analysis. The data collected through the use of a Likert scale required data processing using SPSS, whilst the interviews required a qualitative analytical approach such as thematic analysis. These had not been covered in the course module. It turned out to be an ambitious undertaking! The limited grasp I had of SPSS meant that my data analysis was not exhaustive.

However, using SPSS meant I had a choice in the future between using manual coding or a computer-aided approach. In addition, from a professional perspective, the interviews proved to be a very useful form of interaction with the learners. This was the first time I sat with my physics learners and had honest feedback from them. According to them, they felt valued and included in the whole process of planning their learning. From this MOE-2 assignment, I decided for my IFS study to explore the metacognitive strategies that learners use when solving problems in GCSE physics. The focus was to get beneath the overt problem-solving actions we witness or the processes that produce the solution. The interest was to probe into what actually goes through a learner's mind when confronted with a problem in physics.

My IFS study, *The use of cognitive and metacognitive strategies in problem solving in GCSE physics in a London comprehensive school,* was an attempt to explore how learners solve non-routine physics problems. The objective was to gauge the extent of the deployment or non-deployment of cognitive and metacognitive strategies during the problem-solving process. The argument of the study was based on the importance of the possession of problem-solving strategies, cognitive and metacognitive, for successful problem solving.

This study, conducted in a London urban comprehensive school, involved GCSE physics learners of different academic abilities. As part of the data collection process, the participants solved two problems. These problem-solving sessions were video recorded to produce concurrent verbal protocols, video data and the written answer script. These data were transcribed in the form of a timeline and then coded and analysed for episodes that depicted deployment of strategies and the extent of success in problem solving. This study found positive correlations between metacognitive processing and attainment. The more able students also showed a predominantly forward-working strategy. Low performers showed little metacognitive processing and predominantly a haphazard approach to problem solving.

This stage of my work heralded the beginning of a marked a change in my studies. This was my first time of working with a supervisor at doctoral level. I felt the change in the standard of work ethic and a demand for more time to be spent on exploring issues. I had to meet agreed deadlines, produce high quality work which reflected doctoral standards in terms of depth, and had to be well versed with the concepts I was exploring. This was my first foray into analysing qualitative data using protocol analysis. I had to study every detail in the two seminal texts by Newell and Simon (1972) and Schoenfeld (1985). The IFS phase culminated with me acquiring an in-depth knowledge on protocol analysis and with a clearer focus on what I had to do for my doctoral thesis. On a personal level, I emerged from the IFS study more informed about carrying out a research study, and more focussed and determined to see my doctoral studies through. My IFS success and the feeling that I had a good supervisor buoyed my spirits.

The main doctoral research study was done in an inner London comprehensive school located in one of the south east boroughs, a different setting from the IFS. The target group was a GCE-A level physics cohort. Data were gathered from March to October 2013.

Embarking on the research project brought many challenges I had not envisaged. Theoretically, you have a research project and have it approved by the university and the school. Then you do it! What could go wrong? However, the politics of power within a school and the context present a different reality for practitioner researchers. Despite approval from the school headteacher, it took another month before my line manager approved it.

As observed during the course of this study, the intervention process is steeped in delicate interactions between me, the learners and the influences from within the school and the external environment. These interactions require a careful and cautious approach to ensure progress with the study. Examples that spring to mind include issues of attendance for scheduled interviews, general understanding of the project-related tasks by the students, other demands of the curriculum, procuring recording equipment and the timely embedding of the tasks within the designated curriculum hours. In an inner city school, outside life for post-16 students has a greater priority than staying in school to do extra work unless it's close to examination time. For the scheduled after-school activities with my ten students, I ended up with ten polite excuses!

The depth and intensity of this study which reflects a higher level of engagement with issues was its distinctive approach, a focus on generative mechanisms that sustain successful physics problem solving, grounded within a critical realist theoretical framework. The impact on me academically and at a personal level has been marked and profound. I have realised that critical realism is a philosophical approach that resonates with life. The search for generative mechanisms that sustain social phenomena, even physical ones, seems to pervade many aspects of everyday life. Secondly, the agentic perspective on transforming our reality resonates well with equipping learners with skills rather than knowledge alone and can help them to take conscious decisions. As part of the research process i have produced many learning materials and I find it hard to imagine how I taught physics before I embarked on the doctoral course.

As a professional, the work entailed in producing a thesis has taken me beyond a simple piece of action research as I have also explored further into other issues that impact on attainment and physics learning. I have delved deeper into the impact of self-regulated learning on attainment and the use of context-rich questions in promoting deep learning. This journey has aroused my interest on the real agenda behind a sterile science curriculum. I have also begun to question teacher training courses that do not offer problem-solving courses to trainee teachers, meaning they will resort to traditional approaches. Another more worrying scenario is the lack of meaningful research on physics problem solving in the UK.

My doctoral journey has been a turbulent one with many obstacles, and good things as well. I have had to change jobs four times within a period of three years, get married and have a son without interrupting my studies. This journey has seen me emerging as a different person and has greatly shaped who I am as a person and a professional. Juggling work, study, economic constraints and family commitments has been the furnace that has forged my resolve. I have crossed a threshold in terms of knowledge. I had two options: to quit and make my excuse or to fight for my dream, I chose the honourable one. I trod on towards the academic peak!

1.0 INTRODUCTION

This study focuses on the impact of explicit strategy instruction – cognitive and metacognitive strategies – within a collaborative environment. The focus is on problem solving within an advanced level physics course (GCE OCR A level). Many authors argue that problem-solving strategies must be explicitly taught to learners to enhance problem-solving skills (Schoenfeld, 1985, 2009; Swanson, 1990; Davidson & Sternberg, 1998; Meijer et al., 2006; Jonassen, 2011). Besides the possession of solid scientific knowledge and skills, other variables, metacognitive and affective, also influence the outcome of the problem-solving process at an individual level. The aim of this study was for learners to eventually engage in a conscious deployment of strategies, cognitive and metacognitive, during the problem-solving process. Collaborative group problem solving was chosen as the appropriate pedagogical approach for this intervention. Action research was employed as a way of improving my practice.

1.1 The case for problem solving within the curriculum

Human life, in many ways, is problem solving (Popper, 1999) and the 21st century requires problem solving as an essential skill. In the face of life's challenges, from within us and the environment around us, problem solving is that conscious process we engage in to reach the diverse goals we set to ensure our continual existence. For us humans and many other species, problem solving is a part of our existence, a paradigm of complex cognition that characterises our everyday experiences and involves complex cognitive processes that we are sometimes unconscious of (Gok, 2010). Problem solving emphasises the active nature of thinking, extending cognition beyond simple construction or acquisition of knowledge, to guiding intelligent interpersonal and practical action (Rogoff, 1990). In science, problem solving is an essential tool for predicting and explaining many diverse phenomena (Reif, 2008).

Anderson (2000) asserts that all cognitive activities are fundamentally problem solving in nature. Indeed, Jonassen (2011) argues that the only legitimate cognitive goal of any education is problem solving. Within an educational context, problem-solving is a directed cognitive activity embedded within the learning process and sometimes driving the process.

Problem solving is a process characterised by a complex interaction of factual knowledge, cognitive and metacognitive strategies, experiences, belief systems and social factors (Rogoff, 1990; Taylor & Dionne, 2000). Meaningful problem solving must reflect agency on the part of the learner and hinges on successful near and far-transfer of learnt concepts and skills. Other studies have shown that knowledge created in the context of problem solving is better comprehended, retained and more transferable (Jonassen, 2011). It is on the basis of these arguments, on the role of problem solving in developing higher order cognitive skills, that most physics courses, if not all, use problem solving activities to assess the depth of conceptual understanding. The goal of problem solving within curriculum is to find acceptable solutions and also being able to recognise a similar problem at a later and exert minimal mental effort (Jonassen, 2011).

The focus on physics was based on its nature as a subject and as a matter of personal interest, as I am a secondary school physics teacher. Unlike many other disciplines, physics attempts somehow to capture an element of truth in the physical sense world and then tries to proceed in a rigorous fashion to explain observed phenomena or predict observable phenomena. Physics is viewed as an intellectually deep subject whose learning is steeped in developing problem-solving abilities (Bascones, 1985; Anderson 2000; Abdullah, 2006). Organising one’s problem solving requires strategic learning and problem perception which are evident in the domain of physics (Anderson, 2000). As well as learning major concepts and principles of physics, problem solving skills are considered a primary goal of physics instruction, both in high school and college physics courses (Reif et al., 1975; Redish et al., 2006; Docktor, 2010).

1.2 The focus on GCE physics

Physics drives virtually every sector of the economy that requires specialised intellectual, technical and practical skills applied to solve complex problems using quantitative techniques, the development of technical products and services, and the assembly and operation of highly specialised equipment and facilities. In addition to acquiring transferrable problem-solving skills, studying physics post-16 offers a wide range of university career opportunities.

As from 1996, the steady decline in the post-16 physics course take-up constituted a ´pebble in the shoe’ of policymakers driving the STEM agenda. The number reached an all-time low in 2006 (Murphy & Whitelegg, 2006). However, Mujtaba and Reiss (2012) noted that by 2010 the figure had steadily crawled upwards, though still only to a disappointing 3.6% of the total cohort sitting A-levels, slightly above half of the 1982 figure. Gill (2012) noted an inverse correlation between GCE physics uptake and the level of student deprivation. These studies, amongst others, address broad issues on physics education in the UK. However, research in physics problem-solving, though existent, has not filtered down to the learning-teaching process to make a significant impact on physics learning at classroom level. With view to problem-solving skills, the numerous problem-solving heuristics and strategies proposed have proved to be complex and less popular and have produced fewer results than expected (Schoenfeld, 1985). Chapter 2 will focus on some studies carried out on problem solving, including in the domain of physics.

2.0 LITERATURE REVIEW

2.1 Overview of research on problem solving

Numerous studies to improve competence in physics problem solving through the use of strategies have been undertaken with very little progress on competence reflected within the learning context. The term 'problem' is subject to various definitions; it is a subjective construct that is dependent on the solver's experience and knowledge of the subject. A problem has an element of uncertainty and its solution is a goal-oriented activity where the path or means to the goal is at least somewhat uncertain (Dominowski, 1998).What might seem a routine question for a high achieving learner can be viewed as a problem by a low achieving learner. The widely held view is that, a problem occurs only when someone is confronted with a difficulty for which an immediate solution is not available (Dewey, 1910; Newell & Simon, 1972; Elshout, 1987; Mayer, 1991; Sternberg, 1999; Schunk, 2000; Gok, 2010). From a cognitive information processing perspective, a problem has three parts: the goal, the givens and the obstacles (Anderson, 1985).

Problems can differ vastly, with literature describing two ends of a continuous and subjective spectrum. One end consists of straightforward problems that clearly state the givens and desired goal, and for which all information needed to solve the problem correctly is presented. These are referred to as well-defined problems (Ormrod, 2004; Pretz, Naples, & Sternberg, 2003). At the other end are problems for which the desired goal may be uncertain, some necessary information is absent, or for which there might be several possible solutions. These are termed ill-defined problems. To some extent, whether the problem is well-defined or ill-defined depends on the problem solver's expertise. However, for this study, the problems used will be considered to be well-defined. These are problems found in physics textbooks and examination papers.

Problem solving represents a higher order domain of inquiry which can be described as a form of inquiry learning where existing knowledge is applied to a new or unfamiliar situation in order to gain new knowledge (Sternberg, 1995; Killen, 1996). Problem solving involves a transition from the initial states to the goal states by establishing paths that satisfy the path constraints through the problem space. The process of problem solving is subordinate to executive processes for the management and awareness of one's mental processes to guide this goal directed behaviour (Davidson & Sternberg, 1998). Dewey (1910, cited in Bourne et al., 1979) identifies problem solving as a multi-stage process that consists of recognition of a problem or felt difficulty, location or definition of the problem or the isolation of its relevant features, formulation of possible alternative solutions, mulling over or reasoning through various possibilities to determine the most likely one and testing the selected solution. These stages and the executive processes must be taught to students to develop problem-solving skills. However, the gap between cognitive research and classroom practice is not closing (Larkin, 1980). Most studies have focussed on problems that do not reflect real classroom contexts or the research studies are not implemented well in the actual learning environment.

Despite efforts to map research to practice and investing a time in problem solving, students still demonstrate a surface approach to problem solving, typical of novices. An expert-like approach to problem solving involves an in-depth initial qualitative analysis of the problem prior to working with the appropriate equations. This method of solution for the experts occurs because the early phase of problem solving, qualitative analysis, involves the activation of appropriate schema (Chi et al., 1981). The initial activation of this schema heavily depends on problem comprehension and as a data-driven response to some fragmentary cue in the problem.

Novices typically exhibit a working-backwards approach. They begin solving a physics problem by generating an equation that solves for the desired quantity (Simon & Simon 1978; Larkin et al., 1980). If the selected equation contains an unknown variable, then another equation was selected to solve for this variable. This continued until an equation was selected in which all variables were known. For the GCE-A level examinations, these equations are provided. In addition, novices tend to suggest solutions and equations soon after reading the problem statement, while experts first engage in a kind of qualitative analysis (Larkin, 1979). If novices do spend more time analysing a problem qualitatively, usually they fail to generate a necessary inference or generate faulty inferences (Chi, Glaser & Rees, 1982).

Cyert (1980) attributes the novice approach to a lack of order and general theory to guide students. Rather than a general theory to guide problem-solving, domain-specific problem-solving heuristics, highlighting the role of planning and representation in problem solving, can be developed (Greeno, 1980; Reif, 1980). Other studies have shown that the observed some successes from teaching domain-specific heuristics for mathematics and physics remained localised and could not be replicated (Bloon & Broder, 1950; Woods et al., 1979; Larkin, 1980; Lochhead & Whimper, 1982). The argument of this study is that research must have elucidated the mechanisms of problem solving at a level of detail useful for designing instruction.

Another view is to teach general and powerful strategies in areas like mathematics and physics where the problems are well defined and structured (Larkin, 1980). These strategies include means-ends analysis (Simon & Newell, 1972) and sub-goaling (Greeno, 1976). However, the success of these strategies in physics hinges on a considerable amount of domain knowledge. For example, the means-ends strategy requires knowledge and understanding of the underlying physics, the different equations and certain algebraic manipulations. Heller and Heller (1995) proposed the 'Logical Problem Solving Model' comprising five stages: focussing the problem; explaining the physical principles or laws; planning the solution; executing the solution; and evaluating the answer. This model was adopted for this study.

Reif (2008, p.201) outlines the three fundamental questions that any problem solving strategy must address:

1. How can one describe and analyse a problem so as to bring it into a form facilitating its subsequent solution?
2. How can one make all appropriate decisions that are necessary to construct this solution?
3. How can one assess whether this solution is correct and exploit the knowledge gained from it?

Using physics problems as examples, Reif (2008) further outlines a five-phase, basic problem-solving strategy: describe problem; analyse the problem; construct the solution;

assess the solution; and exploit the solution. Similarities can be drawn between this approach and that proposed by Heller and Heller.

Successful acquisition and the effective use of problem-solving strategies is reflected in the ‘expert–like’ approach to problem solving. At this stage, students will require less time when solving problems as they would have developed automatic processing through a lot of practice (Simon & Simon, 1978). Students will employ a working forward strategy, usually condensing a number of steps into one, with clear, logical and coherent stages that integrate related physics principles (Simon & Simon, 1978; Larkin & Reif, 1979; Chi et al., 1981; Larkin, 1981). Problem-solving strategies cannot be seen as independent of metacognitive strategies (Flavell, 1979) or executive decisions (Sternberg, 1984) hence metacognitive skills must be taught as an integral part of the problem-solving strategy instruction (Flavell, 1977; Pintrich, 2002). It is metacognition about strategies rather than strategies themselves that is essential (Sternberg, 1998).

Executive decisions have global consequences for the evolution of the solution as they determine what solution path to follow or not follow, how resources must be allocated, including time, and when to change the solution path (Schoenfeld, 1985). Metacognition determines the ability consciously to deploy or redeploy intelligently one’s cognitive forces with changing needs and circumstances during any activity (Flavell, 1977). Other literature refers to metacognitive skills as higher-order thinking, a mental activity that involves knowledge and control of one’s own thinking (Armour-Thomas et al., 1992). In a study to clarify the nature of higher order thinking through an analysis of reported knowledge and use of cognitive processes in academic problem-solving situations, Armour-Thomas et al. (1992) focussed on ethnic minority students from low socio-economic backgrounds. In that study, the data did not substantiate the role of monitoring before or during the problem solving process. Armour-Thomas et al. (1992) suggested two possibilities: the process was either inadequately represented in the sample or the participants who constituted the sample were neither aware nor used to this process in their problem-solving process. However, Schoenfeld (1985) argues that competence in problem solving not only hinges on effective deployment of cognitive and metacognitive strategies but on stable conceptual models.

The role of social contexts in knowledge transfer and cognitive development cannot be overlooked when studying cognitive activity as evidenced by earlier research on problem solving (Vygotsky, 1936; Sternberg, 1996; Sternberg & Pretz, 2005). Sociogenesis emphasises the dialectical relationships between the learner and the context in which the learner develops (O'Donnell, 2006). Cognitive development is through social interactions where cognitive processes are modelled before internalisation (Vygotsky, 1988). Social interactions lead to the development of the central and leading functions of all mental development, to the formation of concepts and cognitive schemata, and on the basis of the formation of concepts a series of completely new mental functions (Ratner, 1991).

Due to the socio-cultural nature of knowledge construction many learners from diverse backgrounds display ways of knowing that are sometimes incompatible with the nature of science or the way it is taught in school (Lee et al., 2006). The development of the internal mechanisms of control is anchored in social interactions (Vygotsky, 1978). The argument is, all higher functions originate on the social level then internalised into the individual level. A change in problem-solving of the student, a change viewed as an internal one, is brought about by what Vygotsky (1930) termed 'cultural reconstruction'. This shift requires develops in collaborative context typified by peer and teacher prompting, mastery guidance, rewarding, imitating, and modelling the steps to successful problem-solving. A shift in students is evidenced by solvers having an internal dialogue regarding the way their solution evolve, arguing with oneself at every stage of the solution; planning, strategy selection and deployment and checking of solutions.

Most studies on physics problem solving focussed on university students (Heller & Heller, 2000; Henderson et al., 2001; Kuo, 2004). This study argues that these important skills of problem solving should be taught from an earlier age. Work by; Schoenfeld (1983, 1985a, 1985b, 1987), Lester, Garofalo and Kroll (1989) and Kuo et al. (2005); highlight the effectiveness of using problem-solving frameworks that explicitly emphasise metacognitive processes in teaching problem solving. When learners become successful problem solvers, they spend more time planning the directions that may be taken and monitoring and evaluating their actions and cognitive processes throughout problem solving episodes than do less successful problem solvers.

Key to building competence in problem solving is the view that students can develop from a level of low competence (novices) to a level of high competence (experts). In addition to a solid conceptual base, competence in problem-solving competence can be developed through the instruction of cognitive and metacognitive strategies within a collaborative environment under the guidance of experts. This strategy instruction must also aim to build conceptual and problem-solving schema for later transfer. A further exploration on evidence and impact of schema as the student undergoes the transformation from ‘novice approach’ to ‘expert approach’ is undertaken in the following sections.

2.2 Experts vs. novices: studies in physics problem solving

Studies on experts and novices have focussed on the content of physics knowledge and its mental organisational as a basis for explaining observed process difference. From the point of view of information processing theory, human problem solving involves the problem solver defining the task objectively in terms of the task environment for the purposes of attacking it in terms of problem space. In their study on solving kinematics problems, Simon and Newell (1970) observed that experts showed a superior pattern of problem perception to novices. In a study to compare functional units, knowledge chunks or schemata and how these were accessed during problem solving between novices and experts, Larkin (1978) observed that experienced physicists had more large-scale functional units than novices who accessed principles individually. Knowledge chunks are defined as complex schemata that can guide a problem's interpretation and solution and that constitute a large part of what can be called ‘physical intuition’ (Larkin et al., 1981). Schemata are familiar solution patterns (Schoenfeld, 1985).

The study by Larkin and others on solving physics problems (Larkin et al., 1981) showed that an expert’s memory is structured hierarchically around a small number of fundamental physical principles (i.e. chunks). Jonassen (2011) argues that problem solving is a schema-based activity where learners must deploy and develop schema. Schemata allow a student to categorise the problem and produce a specific response to that problem (Schoenfeld, 1985). Experts also showed strong mathematical skills and strategies for monitoring progress and evaluating their answers. The results from this study indicate the importance of a hierarchical organisation when studying complex domains in physics to promote the building of such large-scale units in learners. This study recommended teaching procedural knowledge and facilitating problem representations to improve expertise within physics problem solving.

Chi et al. (1981) studied how novices differed from experts in representing a problem on the basis of domain knowledge and structure of domain schema. Activation of the schema is the first principal step in problem solving, they argue. Accessing a chunk also cues other useful relations and the procedures or actions to apply those principles successfully (Larkin et al., 1980a; Chi et al., 1981). Schemata for experts contain a great deal of procedural knowledge with explicit conditions for application. In contrast, novice schemata might contain sufficient elaborate declarative knowledge about the physics of a potential problem but lack the appropriate solution methods. From their observations, Chi et al. (1981) also drew conclusions about the content and mental organisation of physics knowledge. In contrast, the novice’s knowledge structures are disconnected and each relation must be accessed individually. There is no clear link between physics principles and application procedures. The traversal through the problem space becomes an inefficient and time-consuming process for the novice (Larkin, 1979).

These studies highlight the desired goal for this study, strategy instruction in physics to bring learners to the level of expert problem solvers and, in the process, aid schema development. Successful problem solving will be evidenced, to some extent, by learners engaging a low detail overview of problem features and expectations (Larkin, 1979; Larkin et al., 1980; Chi et al., 1981; Heller & Docktor, 2009). The effortless weaving of mathematical concepts and use of meta-skills is another indicator of successful problem solving (Larkin et al., 1980; Reif & Heller, 1982; Heller & Docktor, 2009).

The two novice and expert studies reviewed in the preceding sections focussed on the cognitive aspect of problem solving, which forms part of the three components for successful problem solving: the cognitive, the metacognitive and the affective. In addition, these studies were not exhaustive across a range of domains of physics; they focussed on specific areas, mostly in the domain of mechanics (Heller & Docktor, 2009) and so lacked generalisability. In addition, the studies did not consider the context of the study. Discourse formation, knowledge acquisition, encoding and representation in the long-term memory, and its subsequent retrieval for problem solving, are processes influenced by our social contexts (Sternberg, 1999). The deployment of metacognitive skills during problem solving can be used it predict the outcome of the process (Veenman et al., 2006). The role of these control processes is reviewed in the next section.

2.3 Studies on metacognition in problem solving

The use of heuristic strategies in problem solving does not guarantee success unless the solver selects and pursues the right approaches, actively monitors the progress of these approaches and can recover from inappropriate choices. Executive problem-solving skills like predicting, checking, monitoring, reality testing, coordination and deliberate control of attempts to solve problems are attributes of efficient thinking (Brown, 1978).

Metacognition refers to one’s knowledge of cognitive process or anything appropriately related to them (Flavell, 1976). It constitutes metacognitive knowledge (knowledge about tasks, persons and strategies), metacognitive monitoring and regulation. This includes knowing relevant properties of information or data, observing one’s limitations concerning knowledge and realising the need to review certain aspects of work during and after undertaking it. Sternberg (1999) divides metacognition into metamemory skills and other kinds of metacognitive skills. Metamemory skills include cognitive monitoring, which includes self-monitoring and self-regulation (Nelson & Naren, 1994). While self-monitoring is a bottom-up process of keeping track of current understanding, self-regulation entails central executive control over planning and evaluation; it is a top-down process (Flavell et al., 1993).

Distilling the essence of ideas from many expert contributions on metacognition (Flavell, 1979; Brown et al., 1983; Bransford et al., 1999), Pintrich (2002) views metacognitive knowledge as strategic knowledge and defines it as including knowledge of general strategies that might be used for different tasks, knowledge of the conditions under which these strategies might be used, knowledge of the extent to which these strategies are effective and knowledge of self. Metacognition may have many labels –metacognition (Flavell, 1977, 1981), metacognitive strategies (Brown, 1975), metacomponents (Sternberg, 1980, 1999) and higher order thinking (Armour-Thomas et al., 1992) – but the general consensus seems to be that metacognition is the knowledge and control of one's thinking. Regulation of cognition has a positive effect on intellectual performance and its absence has a considerable negative impact. Metacognition helps learners to realise that there is a problem to solve, a need to define it and understand how to reach a solution (Davidson, Deuser & Sternberg, 1994).

Within a physics problem-solving context, knowledge about cognitive tasks is awareness of levels of difficulty of the given problem, demonstrating an understanding of the task demands, selecting an appropriate strategy to deploy, and appreciating a strategy's limitations. This is an instance of self-knowledge, encompassing knowledge of one's strengths and weaknesses, a self-awareness of one's breadth of knowledge base and depth (Pintrich, 2002). Monitoring and self-regulation activities will include; making a plan on how to solve the problem by reviewing available knowledge in view of the task at hand, choosing a strategy, actively reviewing the implementation of that strategy and making changes or checks whenever necessary. These constant checks at certain stages may be triggered by previous experiences of identifying possible errors or realising a quicker way to solve domain-specific problems. This will usually occur to learners who possess certain problem solving schemata. The feeling of sudden realisation of progress or understanding constitutes metacognitive experiences, which are part of metacognitive monitoring (Flavell et al., 1993). The hallmark of a good problem solver's control behaviour is the ability to maintain an internal dialogue on the evolution of their solutions (Schoenfeld, 1985). This is one of the premises for the use of verbal (oral and written) protocols as a data collection method in this study.

From the literature reviewed, problem-solving competence can be increased through teaching students cognitive and metacognitive strategies. From a learning perspective, this requires adopting pedagogical approaches that foster the development of these competences. The design of such a physics curriculum is grounded in the question 'How it is possible to trigger the generative mechanisms involved in competent problem solving?'

instead of ‘What are the strategies that students must be taught to students to improve competence in physics problem solving?’ This view defines the focus of the study, providing a context that enables the student to trigger or disable the generative mechanisms involved in success or failure during the problem-solving process. This places this study within a critical realist perspective. This will be explored further in the sections to follow.

Basing on the premise that learning precedes development, collaboration through cognitive apprenticeship within the zone of proximal development allows the development of internal cognitive structures like metacognitive control skills (Vygotsky, 1978). Due to the social interaction, learners will acquire cultural artefacts in the form of problem-solving strategies, internalising them as part of the cognitive development and then use the internalised knowledge to think and solve problems without the help of others. A socio-cultural perspective on problem solving is important because people‘s understanding of the mathematical (including scientific) enterprise is shaped by their experiences in (and out of) classrooms and it is essential to understand the social processes by which such learning took place (Schoenfeld, 2009). Self-regulation, as evidence of cognitive development will be evidenced by the ability to think and solve problems without the help of others (Slavin, 2009). The final is stage is independent, individual problem solving.

The following sections explore how critical realism and different theoretical perspectives influenced the research methodology on increasing physics problem solving competence. The arguments for choosing critical realism for grounding this study would be expounded. The different theoretical insights will highlight the various generative mechanisms that enable or disable learning geared towards success in problem solving and the intervention strategies that help to develop agency, consequently triggering the desired mechanisms for competence in problem solving.

2.4 Theoretical perspectives on learning that help with problem solving

This section explores how critical realism as a philosophical perspective underpins this study and analyses how the different theoretical perspectives – sociocultural, social cognitive and cognitive information processing theories – interconnect and underpins success in problem solving.

As the universal gunpowder ignition example of critical realism goes, the explosion of gunpowder (outcome) after lighting the flame (action) follows if the chemical composition of the gunpowder is correct (mechanisms) within the right conditions (Pawson & Tilley, 1997). Reviewing the current learning and cognitive development theories helped to develop knowledge and an understanding about the mechanisms (cognitive, metacognitive and collaborative processes) through which action (explicit instruction of strategies) causes an outcome (increased competence) and about the context (collaboration with the zone of proximal development (ZPD) which provides the ideal conditions to trigger mechanisms when solving problems in physics. The ZPD is defined as the distance between the actual development level as determined by independent problem solving and the level of potential as determined by problem solving under guidance or in collaboration with one or more individuals (Vygotsky, 1978). Knowledge of mechanisms which block the effect of the action designed to bring about the desired change is also equally important to possess.

2.4.1 Critical Realism as the philosophical framework

The scientific enterprise of physics research largely produces knowledge through a post-positivist or empiricist approach; however, learning physics within any given educational setting is a social process, one where knowledge construction and acquisition is through meaningful social interactions within a given context. This section seeks to justify the grounding of this study within the critical realist perspective, rather than the post-positivist or constructivist perspective.

A post-positivist epistemology follows the standard Humean view of scientific inquiry that involves empirical observations to gain objective knowledge through the collection of quantitative data by rigorous scientific methods, and then searching for scientific regularities among sequences of the observed events (Sayer, 2008; Robson, 2012). An argument with this value-free approach is that generating generalisable knowledge is built from identifying conjunctions of causal linkages or event regularities rather than from any mysterious causal necessities (Somekh et al., 2012). The post-positivist inquirer sees the world as a series of entities and steady processes, all of which can be fragmented into a series of subsystems (Guba & Lincoln, 1981). Within post-positivism, the assumption is that the inquirer will have no effect on the phenomenon being studied and, equally importantly, the phenomenon will have no effect on the inquirer (Guba & Lincoln, 1981). Causation is understood on the model of regular succession of events. The established empirical regularities between these variables are the basis for formulation of causal laws for prediction and control. The merits of this approach within the physical domain are mirrored by the advances in science and technology, including in physics. However, generalisable laws are questionable for social systems, open systems, where variables cannot be fixed or controlled during the study.

A social setting is a cauldron of vicissitudes such that the ‘laboratory-approach’ of post-positivism in search of generalisable social regularities and patterns lacks depth. Reducing social phenomena to measurable variables to discover causal relationships and generate universal laws casts a shadow on this empirical approach to studying a social system. Hammersley (2012) argues that this approach presupposes that data or facts already exist and are ready to be harvested and that data or facts should be observable, with observability linked to measurability. Unlike in the natural sciences, identifying consistent regularities and establishing causal laws within a social system where complicated events can occur simultaneously at a range of levels is virtually impossible since it requires creating constant external conditions. Social phenomena are intrinsically meaningful; meaning is not only externally descriptive of them but constitutive so meaning has to be understood, and it cannot wholly be measured or counted (Sayer, 2008). The fundamental question for social science must be ‘what properties do societies and people possess that might make them possible objects of knowledge?’ rather than ‘How is knowledge possible?’ (Bhaskar, 1978; Danermark et al., 2002). This represents a shift from epistemology to ontology whereas post-positivism has an epistemological grounding.

An opposing epistemological view to post-positivism is interpretivism. An interpretivist approach takes the view that social phenomena can only be understood by describing the processes by which they are culturally constituted as the things that they are. Interpretivists, constructivists or naturalistic inquirers (Guba & Lincoln, 1982) share the view that the subject matter of the social sciences – people and their institutions – are fundamentally different from those of the natural sciences and find grave difficulties with the notion of an objective reality that can be known (Bryman, 2004; Robson, 2011). Constructionism, phenomenology and hermeneutics are situated within this paradigm (Hamersley, 2006; Robson, 2011). Naturalistic inquirers focus on multiple realities which, like the layer of an onion, nest within or complement one another. These layers, which are intricately related to form a pattern of truth, cannot be described as separate independent or dependent variables (Guba & Lincoln, 1982). Social constructivism focuses on how an individual constructs and makes sense of their world (Robson, 2012). The reality for a group is viewed as multiple, subjective and value-laden. The focus becomes, not the phenomena themselves, and certainly not what might have caused them or what effects they have, but rather the structures or processes by which they are discursively produced by culture members in situ and over time (Hammersley, 2006). In addition, there is a tendency to see the relations between these structures or processes and their products as internal or logical, rather than as causal, in character.

Social phenomena tend to take a fluid construction which cannot be assigned to abstract specific variables or facts as with the positivist approach. This assumption underpins the methodological approaches of interpretivism which consider the use of any qualitative data, and in some instances quantitative data, collection methods which can help in understanding the existing reality. Also, the unstructured nature of the data collection means that the researcher can formulate more research-specific questions out of the data thereby reducing data contamination, while research direction can be changed to reflect emerging data patterns (Bryman, 2004). Other strengths of this value-laden approach include allowing the researcher a chance to view the world through the eyes of the participants, drawing interpretations from the perspective of the participants and a tendency to view social life in terms of processes by probing how events and patterns unfold over time.

Interpretivists and post-positivists disagree as to the generation and nature of social reality. While interpretivism views social phenomena as socially dependent, it does not consider causal explanations (Sayer, 2008). The goal of interpretivism is to appreciate the lived experiences and identify the multiple realities hidden beneath social phenomena. The post-positivist approach to causation does not give a direct answer as to the 'why' and 'how' questions, argues Robson (2012); it seeks for generalisable regularities to social phenomena. Being able to predict is to be able to explain and the ends justify the means in the post-positivist approach which reduces the world to a black box (Lewin & Somekh, 2011). On the other hand, naturalist inquirers fail to grasp those structural and institutional features of society which are in some respects independent of the individual's reasoning and desires and the asymmetries of power which allow some people to advance their ideas whilst other have choices foreclosed (Pawson & Tilley, 2004). These two opposing philosophical stances have their strengths which have been adopted by the critical realists.

The inadequacies of the two opposing paradigms (and their strengths of methods) demand a different philosophical perspective that guides the methodological approach to studying social phenomena. For this study, critical realism as a philosophical lens to answer the issues of the answers to the 'why' and 'how' does competence in physics problem solving evolve and, providing a methodology to confronting situations where research takes place in the field rather than the laboratory (Robson, 2012; Lewin & Somekh, 2011).

Critical realism, which combines realist ontology with an interpretive epistemology (Archer et al., 1998), offers an approach to studying open systems like schools where the researcher has limited control over the study (Robson, 2011). Critical realism posits that there is a world out there independent of human beings and also that that there are deep structures in this world that can be represented by scientific theories. This independent reality can be studied by science and each of us is not making it all up (Bhaskar, 1975). Reality is conceived as being stratified in three overlapping domains (Somekh & Lewin, 2012): the real, the actual and the empirical. The *real* domain consists of structures and mechanisms or tendencies that generate phenomena, both physical and social. According to Bhaskar (1975), the objects and structures of the real give rise to causal powers, called *generative mechanisms*, which causes the events that we may observe (Bhaskar, 1998). These mechanisms, which are usually not observable, may (or may not) trigger events in the domain of the *actual*. The domain of the actual contains aspects which are outcomes of the domain of the real, reality that occurs but may not be necessarily be experienced. Events from the domain of the actual that can be experienced and observed directly or indirectly constitute the domain of the *empirical.* Thus, structures are not deterministic; they enable and constrain events (Archer, 1995; Sayer, 2004).

A causal or generative mechanism implies a relatively deterministic ensemble of characteristics operating together in a predictable and ordered way (Williams et al., 2013). Within the social sciences, these mechanisms are social practices which are outcomes of structures of social relations (Somekh & Lewin, 2012) or the choices and capacities which lead to regular patterns of social behaviour (Pawson & Tilley, 2004). For an intervention that is designed to bring about change, critical realism does nothypothesize whereby the intervention will produce a certain specific outcome, as in positivism. The change generated by the intervention should be viewed as triggered by the release of underlying causal powers of the participants under certain favourable conditions (Pawson & Tilley, 2004). The researcher has to have a theoretical knowledge of such conditions. Structures are intransitive, they operate independently of our knowledge, but our knowledge, a product of our fallible cognitive capacities and ideological pressures of the existing historic-social context, is transitive (Somekh & Lewin, 2012). It follows from these assumptions that critical realism does not aim to uncover general laws, but to understand and explain underlying mechanisms.

With a critical realist grounded study of social phenomena, it is not theory construction that matters but understanding what exists and what do participants do, to whom and with whom do they do it- whether or not individuals have agency. Agency, the capacity to take and exercise control in given social contexts, is determined by the social structures within which they live at that particular socio-historic moment (Somekh & Lewin, 2012). Structure enables and constrains action; human action reproduces or transforms structure; and both agents and structures have causal powers (Somekh & Lewin, 2012). This aspect led to the decision of the intervention as a collaborative activity with students having as much input in the process as is possible. In Bhaskar's transformational model of social action, people as agents produce and recreate structures which later enable or constrain the action of agents (Bhaskar, 1979). For agents to be causally efficacious they must know about the mechanisms they want to trigger, block, subvert or replace to make appropriate causal interventions, for without causality any concept of responsibility and agency is meaningless (Sayer, 2008). Explicit teaching of strategies means students are aware of the mechanisms they want to trigger or suppress.

2.4.2 Sociocultural theory: *A sociogenetic perspective of learning and problem-solving*

The principal assumption of the sociocultural theory is that human cognition is a product of collaborative social activity that cannot be reduced either to physiological processes in the brain or to any individual information processing in the brain alone. Psychological phenomena are viewed to have their origins in social interaction and are organized by social relations (Vygotsky, 1978; Rogoff & Gauvain, 1986). Cognition stretches beyond the individual's isolated mind into cultural systems of artefacts and activities, with the social environment as the facilitator of development and learning (Vygotsky, 1978).

Schunk (2012) maintains that teachers should teach students the tools for problem solving, like strategies and metacognitive self-questioning, and then provide opportunities for using those tools. This is viewed as a better approach to having them construct strategies from an implicit approach. People are considered as agents of their learning and understanding in the acquisition of knowledge (Schunk, 2012). Constructivism posits that people, behaviours and the environment interact in a triadic, reciprocal way (Bandura, 1986, 1997). Within constructivism, the emphasis is on the dialectical relationships between the learner and the context in which the learner develops (O'Donnell, 2006). People are active learners who develop knowledge for themselves through interaction with others and in situations that require acquisition and refinement of skills and knowledge (Geary, 1995; Cobb & Bowers, 1999; Tudge & Scrimsher, 2003; Schunk, 2012).

Cognitive development results from the use and transmission of cultural tools such as language, signs, symbols and problem-solving strategies during social interactions, and from internalising and mentally transforming these interactions (Brunig et al., 2004). During these interactions, guided by adults or more skilled individuals, cognitive processes are modelled before internalisation (Rogoff, 1990).

Initially, through cooperative group activities and cognitive apprenticeship, the teacher models the deployment of the strategies, providing structure and guidelines on how to accomplish the problem-solving task, demonstrating the proper expected performance of successfully solving problems. Students can model statements to guide action in the form of questions like: ‘What is it I have to do in this problem?’, ‘What aspects do I need to pay attention?’ and ‘How am I doing so far?’ (Meichenbaum, 1977). Strategy mastery hinges on frequent, timely and focussed feedback on students progress. Scaffolding is gradually removed as competence increases and activities become predominantly collaborative.

A. Implications for strategy instruction

Drawing from Luria´s argument on verbal control of motor behaviour (1961), competence in physics problem-solving can be improved through private speech, verbalising rules, procedures and strategies during problem-solving. Private speech follows an overt-to-covert developmental cycle, and speech becomes internalised earlier in students with higher intelligence (Berk, 1986). Based on this idea, during instruction of strategies, students who often experience difficulties can be taught to initially overtly verbalise the questioning strategies and the metacognitive prompt questions as part of a scaffolded process. To facilitate transfer and maintenance of the strategies to internal structures, overt verbalisation is then eventually faded into a whisper, then to a covert level to become internal self-regulating speech (Schunk, 1999).

A cooperative approach can be used initially, where roles are fixed and later developed into collaborative with students assuming various role as the problem solving evolves. The group structure has to support meaningful interactions within the zone of proximal development (ZPD). In physics problem solving, this would represent the problems students cannot solve on their own but can solve when they work with one or more able individuals. Working within this zone, through guided participation the teacher and the student will discuss and implement the problem-solving strategies using different examples as models (Rogoff, 1986).

Guided participation can include routine activities, tacit as well as explicit communication, supporting structures of novices' efforts, and transfer of responsibility for handling skills to novices (Rogoff, 1990). A group of apprentices will serve as peer resources for one another, aiding and challenging one another with the more competent problem solver as the 'expert' who will develop breadth and depth of skill in carrying out the activity and guiding others. The teacher's role will involve: recruiting the student's interest in the problem; sub-goaling the task; maintaining pursuit of the goal through motivation and direction of the activity; giving feedback through marking critical features of discrepancies of the student-produced and the ideal solution; controlling risk of frustration; and demonstrating an ideal version of the solution (Wood, Bruner & Ross, 1976).

B. The mechanisms and contexts

From the sociocultural perspectives, the contexts for a positive shift in problem-solving competence include:

i. Cognitive apprenticeship – where the teacher or more able individuals provide scaffolding through clues, reminders, encouragement, breaking the problems into steps, providing examples and modelling the use of cognitive and metacognitive strategies. These forms of support are gradually withdrawn as each student progresses.
ii. Collaboration within the ZPD – which allows co-construction through sharing of different approaches like peer-assisted deployment of strategies such as peer tutoring, reciprocal teaching and collaborative cooperative learning (Palincsar & Brown, 1984; Rogoff, 1990; Slavin, 1995).

The mechanisms which are triggered include:

i. Argumentation – a central aspect of social exchange which involves a divergence of understanding, followed by group efforts to resolve and reach a shared understanding (Miller, 1987).
ii. Appropriation – students bring forth their ideas to the collaborative activity, consider alternatives, and recast these ideas in an effort to build an individual

understanding. The shared knowledge is taken in to extend the existing knowledge structures (Rogoff, 1990).

iii. Private speech – a mechanism for the appropriation of shared knowledge and self-regulation (Rogoff, 1990; Slavin, 2009). Private speech, self-talk (overt verbalisation) or inner speech (covert verbalisation) illustrates the internalisation of the acquired cognitive tools, i.e. the use of language and problem-solving strategies.

iv. Individual agency – the active role of the individual student during collaboration is inseparable from the context and determines the context (Rogoff, 1990). Agency, though socially organized, is exercised through individual acts of thinking, evaluation, analysis, synthesizing and abstraction. The individual contributions lead to the construction of new meanings thereby modifying existing socially constructed ones.

These mechanisms and contexts, though explained separately, are intricately intertwined. To illustrate, argumentation occurs during collaborative problem solving and involves the ´interlocking´ of individual thoughts, changing the individual thoughts of each participant, the result-a shared understanding is then appropriated by each student (Rogoff & Buavain, 1986; Lawrence & Valsiner, 1993).

Summarily, from a critical realist perspective, competence in problem solving (arriving at the outcome) from explicit teaching of strategies (action) through cognitive apprenticeship (Wood, Bruner & Ross, 1976) and peer-assisted learning (mechanisms) will be possible if these are developed through collaborative group problem-solving activities within the learners' zones of proximal development (contexts). For a summary of all three theoretical frameworks, see appendices 1-3.

2.4.3 A sociogenetic perspective: Social Cognitive Theory

Social cognitive theory (SCT) posits that human agency acts generatively and proactively, rather than reactively (Bandura, 1999). Human adaptation and change is viewed as rooted in social systems where personal agency operates within a broad network of social influences. Agency manifests in three forms: direct personal agency; proxy agency by relying on the efforts of intermediaries; and collective agency, operating through shared beliefs of efficacy, pooled understanding, group aspirations and collective action (Bandura, 1999). Collective agency identifies humans as social entities who also extend their personal agency to collective agency through collective power to produce desired outcomes. Cognitive growth, which influences success in problem solving, can be viewed as a consequence of the active co-participation of sociocultural activity and conscious personal construction.

Exercising personal agency within a social context includes transactions through mechanisms such as self-organisation, being proactive, self-reflectivity and self-regulation. Students are viewed as products as well as producers of social systems. Socio-cultural and personal determinants are treated as co-factors within a unified causal structure.

As active agents, students have active and creative roles in their own cognitive development, at both personal and collective levels (Fischer & Biddel, 1997). Agency can be by proxy, i.e. through the efforts of others, or by collective agency, operating through shared beliefs of efficacy and collective action (Bandura, 1999). In developing new approaches to solving problems students will develop new cognitive and metacognitive structures which might in turn require a change in the approach to the learning process. The bi-directional process between cultural systems and intellectual development means a simultaneous construction of new personal and cultural systems, sometimes challenging existing systems.

Realisation of agency requires self observations on how outcomes flow from action and recognition that actions are part of oneself within a social activity. Agency means the student continually creates new relationships between multiple levels of cognitive and environmental systems through the integration of new skills and knowledge into the cognitive system, which in turn extends out onto systems of socially patterned activists (Fischer & Biddel, 1997). Figure 2.1 illustrates the role of agency in the bidirectional reciprocal causation between internal events (cognitive, affective and metacognitive), behaviour and external (environmental) events.

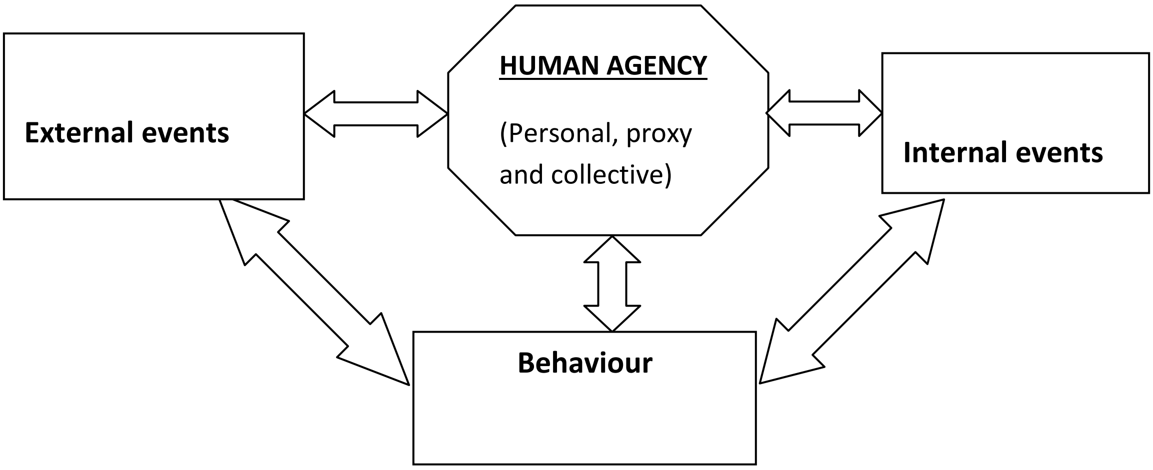


Figure 2.1: The role of agency in the bidirectional causal reciprocality between external and internal events

A. Key mechanisms from a SCT perspective

Transformation of thought into proficient action, regulation of motivation and action, and self-efficacy are the mechanisms of diffusion of new styles of behaviour (Bandura, 1986, 1994, 1999). The development of cognitive competencies, including problem solving, results from the transformation and processing of information derived from enactive experiences, social guidance and modelling. These are integrated into cognitive models that serve as guides for reasoning and action leading to proficient competence.

Bandura (1999) identifies *concept-matching* through monitored enactment as the main mechanism for converting conceptions to skilled action. Cognitive guidance with feedback provided during the explicit teaching and modelling of strategies will help in detecting and correcting mismatches between conception and action (Bandura & Carroll, 1987, 1990; Bandura, 1999). Continued practice will ensure that practised problem-solving strategies become fully integrated and executed with ease, translating to efficient functioning, and a mix of routinised and mindful action.

Human motivation and action are extensively regulated through the *anticipative mechanism of forethought* (Bandura, 1999). Human motivation is cognitively generated when people motivate themselves and guide their actions anticipatorily through the exercise of forethought (Bandura, 1987). Forethought, translated into incentives and courses of action through the aid of self-regulatory mechanisms, brings the projected future into the present when conceived future states are converted into current motivation and regulators of behaviour. Anticipated likely consequences of prospective actions allow goal setting and planning. The anticipative mechanism of forethought has a pivotal role in the decision to engage or not with a given problem and the planning stage of problem solving.

Much motivation and behaviour is regulated anticipatorily by outcomes expected from a given course of action (Feather, 1982; Bandura, 1986, 1999). While outcome and goal motivators are perceived to act through the mechanism of anticipation, cognitive motivation is based on cognized goals, outcome expectancies and causal attributions. Causal reasons conceived retrospectively can also affect future actions anticipatorily by altering judgements of personal capabilities and perception of task demands. These variant forms of cognitive motivation are acted upon by the *self-efficacy* mechanism of personal agency (Bandura, 1997). Self-efficacy beliefs shape self-regulation of motivation and causal attributions as people construct knowledge and engage with tasks.

Self-efficacy refers to personal beliefs about one's capabilities to learn or perform actions at designated levels (Bandura, 1977). Self-efficacy has influence on choice of activities, effort expenditure on a chosen task, persistence and achievement (Schunk & Pajares, 1997; Pajares, 2005; Schunk, 2012). Self-efficacy information in a given domain is acquired from one's performance, observations of models (vicarious experiences), forms of social persuasion and physiological indexes (e.g. anxiety high heart rate, sweating).

Self-efficacy is a key factor in the generative system of human competence argues Bandura (1997). The generative capacity of self-efficacy allows for the effective organisation and orchestration of the cognitive, social, emotional and behavioural sub-skills. Self-efficacy influences people whether they will attempt to make things happen or not (Bandura, 1999). Perceived self-efficacy is not about the skills and knowledge a student possesses but about the student believing they can successfully deploy these skills and knowledge to successfully solve a given problem. Possession of good problem-solving strategies can be overruled by self-doubts; hence, effective functioning requires both skills and efficacy beliefs to use them well. Students who regard themselves as efficacious will do well in physics problem solving as was evidenced by a study on mathematics problem solving (Collins, 1982).

A study by Bouffrad-Bouchard et al. (1991) showed that causal attributions of self-efficacy to cognitive competencies were independent of intellectual performance. If students of same cognitive ability are given a difficulty problem to solve, those with a high sense of self-efficacy are likely to outperform those with a low sense of self-efficacy, and raising the beliefs of those with low self-efficacy makes them more persistent and perseverant (Bandura & Schunk, 1981). Children with higher self-efficacy are quick to notice and discard faulty strategies, have better time management skills, are more persistent and less likely to reject correct solutions prematurely, have greater strategic flexibility and are more accurate in evaluating the quality of their performances (Collins, 1982; Bouffrad-Bouchard et al., 1991). Self-efficacy has a powerful influence on individuals’ motivation, achievement and self-regulation (Bandura, 1997; Schunk & Pajares, 2009). Students with high self-efficacy will strive to complete a challenging problem while those with low self-efficacy will avoid the task, especially after encountering a small difficulty. This observation is used later in the study to gauge participants´ self-efficacy.

Students acquire self-efficacy information from actual performances, vicarious (observational) experiences, forms of persuasion and physiological symptoms (Pintrich & Schunk, 2002). On this premise, intervention strategies aimed at building self-efficacy have to focus on these sources of information. These strategies have already been discussed in section 2.4.1. The process of gaining self-knowledge to build conceptions of self-efficacy requires metacognitive skills for self-monitoring of knowledge for a given task, the task goals and strategies. Academic learning is self-regulated through metacognitive skills (Flavell, 1979; Brown, 1984). Metacognition is viewed as cognitive appraisal and control of one’s cognitive activity, thinking about the adequacy of one’s thinking.

Self-regulation is through self-efficacy, attributions, learning strategies and self-evaluations which reciprocally interact (Schunk, 2012). From this sociogenetic perspective, metacognitive skills are developed and internalised during through social interaction. The execution or non-execution during problem solving of these internalised processes reflects agency. Self-efficacy mediates the choice of task-related cognitive strategies, structuring problems in ways that specify goals and possible routes to them, selecting appropriate strategies and applying them effectively to solve the problem. Students monitor their regulative thought, evaluate its adequacy in the solution of problems and, if necessary, make corrective adjustments. This builds efficacy beliefs!

Self-efficacy beliefs are both products and determiners of peer affiliations (Bandura, 1997). Peers can influence personal efficacy for academic pursuits by influencing interpersonal affiliations through selective association. Social comparisons influence self-efficacy beliefs through their mediating mechanisms: level of effort, perseverance, cognitive efficacy, choice predilections, and stress and demoralisation. Peers contribute to the social development and validation of self-efficacy in several ways. In receiving comparative feedback on performance from peers and teacher, students develop self-appraisal for each other. Shared social appraisals serve as persuasory modes of influence on beliefs and self-efficacy (Marshall & Weinstein, 1984). Individual self-appraisal is built from peer appraisal. Peers learn from each other by direct tutelage and modelling of academic proficiencies (Schunk et al., 1987). This is a key idea when formulating a context for the intervention, collaborative group problem-solving rather than just group works.

B: Developing problem-solving competences from a SCT perspective

Problem-solving competence as cognitive development is through exploratory experiences, modelling and instruction with a gradual improvement through self-appraisal skills. This development requires sustained involvement in activities, and in appropriately structured activities such experiences provide mastery experiences required to build intrinsic interest and a sense of cognitive efficacy. This places a limit on the minimum time for the intervention period. Gained self-knowledge from feedback serves as a basis for judging success or failure in future endeavours.

Students develop self-motivation through setting of personal challenges in the form of achievable proximal goals which provide immediate incentives and guides for current pursuits. Efficacious self-regulators invest activities with proximal challenges on their own by adopting goals of progressive improvement when they can get feedback on how they are doing. Sub-goaling serves as a cognitive indicator and vehicle for developing a sense of personal efficacy. Long goals are sub-divided into a series of attainable goals to guide and sustain one's efforts along the route (Bandura, 1997). For GCE-A level students, short term goals vary from mastering concepts to achieving target grades in each sub topic or module. These lead to the long term goal of attaining the entry requirement for the desired graduate course.

SCT views *guided mastery* as the principal vehicle for the cultivation of competencies (Bandura, 1986, 1997), similar to scaffolding (Bruner & Ross, 1976) and tutoring by social guidance (Vygotsky, 1962). Modelling, a critical component in SCT refers to behavioural, cognitive and affective changes deriving from observing one or more models (Zimmerman, 1977; Rosenthal & Bandura, 1978; Schunk, 1998). Cognitive modelling and instruction aids are used to convey the strategies and relevant procedural knowledge in graduated steps through guided practice with incentives and personal challenges embedded to ensure self-involving motivation and continual improvement through feedback. The sequence of cognitive modelling is as follows: cognitive modelling; overt guidance; overt self-guidance with self-talk to guide oneself; faded overt self-guidance with the learner whispering self-instructions; and covert self-instruction where problem-solving is guided by inner speech (Schunk, 2012).

A key function of modelling related to problem solving is observational learning, when new behaviours that could not have been observed prior to the modelled behaviour, despite high levels of motivation, are observed (Schunk, 2012). Observational learning comprises four processes: attention, retention, production and motivation (Bandura, 1986). The student's attention is directed by physically accentuating relevant strategic features, subdividing the strategies into parts and complex activities into tasks, using competent strategies to model and demonstrating the usefulness of chosen strategies over a wide range of contexts. Retention is increased by rehearsing problems with similar structures and relating new problems to ones that have previously been solved.

Production involves practising modelled problems, with corrective feedback and re-teaching to refine the rough approximations acquired during observation. The modelling process can be extended to include errors in the model to help students identify typical errors. The teacher will model and explain problem-solving with chosen strategies, followed by cooperative group problem-solving sessions. The teacher acts as a guide with instructions, cues or questions, gradually reducing the guidance with time.

During problem solving, students develop intellectual efficacy through peer modelling of strategies, social comparison with performance of other students, and instructor interpretations of children's successes and failures in ways that reflect favourably or unfavourably on their ability (Schunk, 1984; Schunk & Swartz, 1993). Repeated verification of the mastery of strategies and their role in achievement through feedback to the learners will raise their personal efficacy (Schunk & Rice, 1992).

Strategy deployment is partly mediated by one's self-efficacy or collective efficacy. Using the self-regulation function of speech, students can guide the appropriation process by converting verbal instruction to overt speech and eventually covert-self instruction (Luria, 1961). Self-directed mastery experiences are then arranged to strengthen and generalise a sense of personal efficacy. By structuring cognitive modelling and self-directed mastery in such a way that develops self-regulative capabilities for exploratory learning and strengthens students' beliefs that they can exercise some control over their intellectual self-development, the evolvement of agency is accorded primacy. Self-regulation is reflected through the conception-matching process for transferring knowledge structures into proficient performances. The student compares current knowledge against the level of understanding one seeks and then acquires the requisite knowledge that constitutes the desired level.

Peer modelling can alter self-efficacy beliefs through social comparison as knowledge of modelled successes by social equals boosts individuals' appraisals of their own capabilities, whereas modelled failures leave students anxious. The knowledge that other peers using the same problem-solving strategies have achieved high levels of success will influence students to perform better through the use of such strategies (Schunk & Gunn, 1985). Tutoring, in the form of more able peers with a higher self-efficacy serving as instructional agents to demonstrate skills, operations and strategies in problem-solving, can be used to develop strategies. Within collaborative groups, a mentoring approach which incorporates mutual learning can be more effective with more able peers sharing their skills and problem-solving strategies (Johnson, 2006). Not a practical distinction can be drawn between intervention these strategies and those proposed for the sociocultural framework.

2.4.4 The *cognitive information processing (IP) perspective*

IP theories extend learning beyond the influence of environmental factors, including social activity. Learning is extended to what individuals do with the internalised information, how they attend to it, rehearse it, code it, integrate it, store and retrieve it for transfer. Information Processing theories highlight specific processes involved during cognitive processes whose function is under the control of executive processes which regulate the flow of information throughout the information processing system (Siegler, Deloache & Eiseberg, 2006). Information-processing models which have the working memory as their central concept will be the focus of this literature review. Problem solving is one of the most important types of cognitive processing that occurs during learning (Schunk, 2012). Problem solving, from an information processing perspective, is viewed as an interaction between a task environment and a problem solver who is thought of as an information-processing system (Newell & Simon, 1971; Kahney, 1986; Jonassen, 2011).

Problem solving within the IP framework is viewed as a directed and personal internal cognitive process involving the representation and manipulation of knowledge, in the problem solver’s cognitive system, to achieve a goal when no solution method is obvious to the solver (Mayer & Wittrock, 2006). This process involves understanding processes and search processes (Simon & Newell, 1972). Problem-solving skills develop in three stages (Fitts & Posner, 1967; Anderson, 1985): the cognitive stage, the associative stage and the autonomous stage. During the cognitive stage, participants develop declarative encoding by committing to memory a set of facts relevant to the skill, usually through rehearsal. In the associative stage, firstly there is gradual detection and elimination of errors developed in the first stage; secondly, the connections among the various elements required for successful performance are strengthened. In the final stage, the autonomous stage, the procedure becomes more and more automated and requires fewer processing resources.

A. *The working memory and problem solving*

The working memory model describes the cognitive process through which the learner acquires and processes new information to solve the encountered problem (Baddeley, 1986; Baddeley & Logie, 1999; Cowan, 1999). Baddeley´s multi-component model of working memory (WM) has the following four subcomponents (Baddeley, 2003): (1) the central executive, which is an attention-controlling system that is responsible for directing attention to relevant information, suppressing irrelevant information, and coordinating two slave systems, i.e., the phonological loop and the visuospatial sketch pad; (2) the phonological loop, which consists of a phonological store that can hold memory traces for a few seconds and an articulatory rehearsal process that is analogous to subvocal speech; (3) the visuospatial sketch pad, which handles visual images and spatial information; and (4) the episodic buffer, which is a limited-capacity store that binds information together to form integrated episodes that is assumed to be under the attentional control of the executive.

The Cowan WM model (Cowan, 1999) is an embedded-process model. This model assumes that WM is a part of long-term memory and that the memory system is operated via the interactions between attentional and memory mechanisms. In addition, WM is organized into two embedded levels (Cowan, 1999). The first level consists of activated long-term memory representations. Information in the memory system can be held in activated or non-activated states; when in non-activated states, these elements represent long-term memory (LTM).

Studies have suggested that WM span is related to the ability to solve difficult problems (Song, He, & Kong, 2011). Success in problem solving can be predicted on the ability to maintain goals, action plans, and other task-relevant information in a highly activated and accessible state, and when necessary, to inhibit activation of irrelevant or distracting information (Hambrick & Engle, 2002). The ability to maintain information in a highly activated state via controlled attention may be important for integrating information from successive problem-solving steps, including the construction and manipulation of mental models. The working memory capacity determines how many representations can be brought into the focus of attention simultaneously, allowing one to hold in mind knowledge and relevant information, maintaining this relevant information in an active and accessible state (Dietrich, 2004). Working memory capacity limits the amount of information which can be concurrently processed; performance on science problem-solving tasks is expected to drop when the information load exceeds students' working memory capacity (Johnstone & El-Banna, 1986; Omrod, 2006). Other factors include; problem encoding, depth and integration of relevant knowledge, long term memory retrieval and metacognitive awareness.

From the working memory perspective, a student is likely to be successful in solving a problem if the problem has a mental demand (Z demand) which is less than or equal to the subject's working-memory capacity (X), but fail for lack of information or recall, and unsuccessful if Z>X, unless the student has strategies that enable him/her to reduce the value of Z to become less than X (Johnstone & El-Banna, 1986, 1989; Sweller, 1994). WM capacity is also considered as a prerequisite for cognitive flexibility, strategic planning, and speed with which information is transferred to long-term memory (Baddeley, 2000; Dietrich, 2004; Cowan, 2010). Studies on the association between limited working memory capacity and information load in problem-solving provided support for the positive relationship between working memory and science achievement (Solaz-Portolés & Sanjosé, 2007).

The existence of knowledge in the form of principles, examples, technical details, generalizations, heuristics, and other pieces of relevant information is a primary requirement for success in problem solving (Stevens & Palacio-Cayetano, 2003). Another requirement, I suggest, is their interconnectedness in the form of schema. The literature reviewed identified certain closely interconnected mechanisms that must be triggered to guarantee the success of an intervention process on improving problem-solving competence. These include; schema construction, retrieval, automation, control of attention, fixation, transfer and metacognitive processes. The following section explores three of these; schemata construction, metacognitive processes and transfers.

B. Mechanisms in problem solving: An IP perspective

The most critical phase of the problem-solving process is the construction of a mental representation of the problem in its context (Jonassen, 2011). Through the constructed model, the solver establishes the links between the problem description and the underlying knowledge base (Heyworth, 1998). However, the construction of a mental model is often schema driven since the existence of schema enables the recognition of different problem states that invoke certain solutions (Schoenfeld, 1985; Sweller, 1988; Jonassen, 2011). The possession of a complete schema for any problem type means the construction of the problem representation becomes simply a matter of mapping an existing problem schema onto the problem to be solved, in most cases. Schema activation methods include generative methods such as: elaboration, summarising, self-explaining, questioning, guided discovery and apprenticeships.

A schema or organised memory network is a tightly organised set of facts related to a particular object or phenomenon (Schmidt, 1975; Rumelhart & Ortony, 1977). A problem-solving schema is an existing framework used to identify the type of problem being solved. These mental frameworks help to organise knowledge to create a meaningful structure of related concepts within a specific domain (Sternberg, 1999). Chunks are the building blocks for problem schemata. A chunk is any perceptual configuration that is familiar and recognizable, a single symbol of encoded information (Simon, 1980; McClelland & Rumelhart, 1981). Schemata can then be viewed as interconnected chunks. A schema consists of semantic information and situational information (Rumelhart & Ortony, 1977; Jonassen, 2011). Problem-solving schemata are a result of previous experiences of extracting and applying domain knowledge in solving particular type of problems. Problem-solving schemata help to address the limitations of working memory and usually lead to automatic processing of problems.

An improvement in the problem-solving competence is evidenced by a possession of a large number of chunks in the long-term memory (Schoenfeld, 1985). Deep categorisation of problems will allow schema construction. Students are tasked to categorise problems into domains (structural categorising) and classifying new problems consistently with prior categorisations from previously solved problems. Schema building during learning will allow transfer (Matlin, 2009; Schunk, 2012).

Studies have also shown the importance of a continuous interplay of cognitive and metacognitive behaviours for successful problem solving and maximum student involvement (Artz & Armour-Thomas, 1992; Teong, 2003). Effective metacognition means:

identifying one or more goals that represent the problem solution; breaking a complex problem into two or more sub-problems; planning a systematic, sequential approach to solving the problem and sub-problems; continually monitoring and evaluating progress towards a solution; identifying any obstacles that may impede the progress of the chosen strategy; and devising a new strategy if the current one is not working. Metacognition is dependent on the conceptual understanding of the subject matter. Students who can develop the ability to ascertain when to make metacognitive decisions, and elicit better regulated metacognitive decisions will outperform those of a similar ability but do not elicit metacognitive decisions when solving problems (Teong, 2003). However, possession of schemata of procedural and domain knowledge, including metacognitive strategies, without successful transfer, another mechanism involved in problem-solving competence, will not result in successful problem solving.

Transfer lies at the heart of problem solving in new contexts when; knowledge, skills and strategies are applied in new ways, with new content, or in situations different from where they were acquired (Schunk, 2012). Transfer is the application of knowledge from one situation to another (Chen & Klahr, 2008). It involves change in the performance on a task as a result of the prior performance on a different task (Gick & Holyoak, 1987). Transfer of strategies responds to the mechanisms of cognition: encoding, storage and retrieval. Retrieval and transfer depend on the way the knowledge was encoded, organised in the memory (Tulvig & Thomson, 1973; Sternberg & Frensch, 1993). Retrieval depends on whether the information to be retrieved is tagged as relevant for the given recall. Discrimination affects transfer by tagging an item as either relevant or not relevant to a new situation in which that item might be applied (Anderson & Bower, 1973; Sternberg & Bower, 1974).

C. Strategies to increase physics problem-solving competence: An IP perspective

Experienced solvers rely more on conceptual models of the problem’s structural characteristics than quantitative models represented in formulae (Chi et al., 1981). Schema building can be enhanced by studying problems solved during the modelling process, worked examples. To enhance schema construction and transfer in physics problem-solving, students must include a conceptual model for each problem being solved because it is the quality of the conceptual model that influences the success of problem solving (Hayes & Simon, 1976; Jonassen, 2011). Conceptual models in physics include Newton's Laws, conservation of momentum, two-directional motion of projectiles of projectiles, etc. Another approach is structural analysis by analysing different examples for the same type of problems promotes a deeper cognitive understanding. For structural analysis, students must use existing problem-solving schemata to categorise new problems from different domains.

Constructing a structure a map for each kind of problem is another approach to enhance schema building. In physics, the relationships that define most problems are causal (Jonassen & Ionas, 2008). Rather than giving numerical procedures which may be memorized and used without understanding, a task that requires constructing structure maps requires exploring the causal links and conditions that are stated in the problem statement. This can be achieved using text-based or diagrammatic stimuli that require knowledge of underlying concepts or basic theories of physics can be used (Neto & Valente, 1997).

Other approaches that can be embedded in problem-solving strategies to enhance schema building include:

i. The use of question prompts that focus on problem structure and situation, e.g. in what domain or domains is this problem? What laws or principles are applicable to this scenario? What physical quantities are involved in this scenario? How do these quantities vary? What are the situational constraints of the problem? What physical relations in the form of equations are important?
ii. Text editing for assessing the quality of problem schemas (Ngu, Lowe & Sweller, 2002). A physical quantity can be added or removed, a concept improperly presented or an equation improperly written. Students must identify whether the problem is correctly presented and justify their identification. Unless students understand what kind of problem it is and what elements are appropriate for this particular kind of problem, they will not be able to solve it (Jonassen, 2011).

iii. Problem classification of given problems and comparing the degree of similarity is one way of building schemata (Littlefield & Rieser, 1993); alternatively, the problems can be sorted into groups based on physics concepts and principles.

iv. Analogical encoding, where students compare and contrast pairs of problems for structural similarity. The effort is to help students understand structure rather than surface characteristics of problems (Chi et al., 1981; Hardiman, Dufresne & Mester, 1989).

Reducing working memory demands during problem solving can be another approach to improving WM capacity. Approaches include; reducing the linguistic complexity of problem statements, sub-goaling the problem, use effective strategies through heuristics. Strategy use like deploying algorithms aims to reduce the mental demand of a problem without changing its logical structure (Omrod, 2011). This can facilitate student success by decreasing the amount of information required for processing, thus avoiding working memory overload (Níaz, 1987). Another approach is reducing the problem statement to a labelled diagram and also creating an external record like writing the data (Johnstone, Hogg & Ziane, 1993; Omrod, 2011). An example is drawing a vector diagram to represent projectile motion. Expert problem-solving performance depends on the amount of deliberate practice (Ericson, 2003).

Deliberate practice enables learners to get around the limited capacity of working memory by developing the prospect for a long-term working memory whereby relevant information is stored in the LTM and retrieval cues are held in STM (Ericson & Kintsch, 1995). Learning some key processes to automaticity, learning them to a point where they can be retrieved quickly and easily is another approach (Mayer & Whittrock, 1996). Skills that can be taught to automaticity in physics problem solving include: basic mathematical operations like ‘change of subject’, inspection of units, labelling graphs, conversion of numbers to standard form and degrees of accuracy.

Transfer can be viewed as a mechanism that must be enabled for successful problem solutions with supporting mechanisms of encoding, storage (chunk and schema formation), integrating, organising and retrieval. During transfer, memory activation for the retrieval of the prior knowledge is initiated by the task cues as the input information is cross-referenced with propositions linked in memory (Anderson, 1990). However, the success of transfer is determined by well-organised schemata on domain knowledge and on problem-solving. Successful transfer depends on task similarity (superficial and structural similarity of problems), context similarity and the time interval (Chen & Klahr, 2008).

Teaching to enhance strategy transfer in problem solving will involve three phases (Phye & Sanders, 1992; Phye, 1992, 2001). In the first phase learners receive instruction and assessment of their metacognitive awareness of using the strategy; the second phase will involve further practice on training materials and recall measures; in the final phase, students attempt to solve new problems with different surface characteristics but same deep structures. Transfer of problem-solving strategies will include cueing retrieval and generalizability (Schunk, 2012). When cueing retrieval, students must realise which stored knowledge will help with the given task through question prompts or help from the teacher or group peers during collaborative group problem sessions (CGPS) . As competence improves, cueing must be derived from the problem statement. To promote long-term retention and transfer, students must practise problem-solving strategies in varied contexts, ensuring that they understand different links of knowledge to build schemata in the LTM (Halpern & Hakel, 2003).

Activities that involve identifying key features of certain problems help to develop structural encoding. Problem encoding affects retrieval and memory activation, which consequently affects transfer. The initial encoding of the problem determines where and how of the search in the LTM during retrieve .Failure to encode means failure to solve the problem. Strategies include solving problems through modelling or drawing pictures (Weinstein & Mayer, 1986; Schultz & Lockhead, 1991). Retrieval is based on two processes: recognition or association, with the latter being slower. Recognising that a similar problem has been solved before is evidence that an information structure is stored in the LTM. The process of retrieval is based upon the spreading of activation among concepts or items of knowledge in memory (Ohlson, 1992). Successful retrieval depends on use of appropriate cues for direct retrieval or retrieval of an appropriate strategy.

Generalisability is enhanced by providing students with opportunities for near transfer through solving structurally similar problems and then gradually increasing the complexity of the problems to facilitate far transfer. Other strategies include load reducing methods to free working memory capacity and building problem-solving schema (Mayer & Wittrock, 2006). Analogical transfer involves recalling a problem solved previously with a similar structure (Singley & Anderson, 1989).

Self-regulation refers to instigating, modifying or sustaining cognitive activities oriented toward the attainment of one's goals (Schunk, 2003). In most cases, students fail to plan during problem solving due to the failure to inhibit the desire to solve the problem immediately or by being over optimistic (Siegler et al., 2011). However, the metacognitive control decisions to self-regulate during problem-solving through conscious actions of orientating, planning, monitoring, executing, and monitoring and evaluation highlights the agentic role of the solver. Teaching specific cognitive and metacognitive skills will develop good strategy users who can evaluate whether the strategies they have chosen are producing progress towards chosen goals. Self-regulated learning strategies can facilitate transfer (Schunk, 2012; Fuchs et al., 2003).

Metacognition during problem solving can be enhanced by asking students to explain their problem-solving approach – what they are doing and why they are doing it. In addition, students can be asked questions to guide and evaluate progress during problem-solving such as 'Are we getting closer to the goal?' and 'Why is this strategy most appropriate?' (Kramarski & Mevarech, 2003).

Approaches to raising competences of these cognitive mechanisms are grounded within the sociocultural and social cognitive perspectives discussed earlier (sections 2.4.1 and 2.4.2). These include apprenticeship methods of modelling, coaching, scaffolding and reciprocal teaching within a collaborative group problem-solving context.

2.4.5 The emerging theoretical framework

Though generated from different perspectives, all learning theories aim to produce an enduring change in behaviour in those involved through practice or other forms of experience. The view that these different theories can be integrated to give a full picture of the internal and external generative mechanisms formed the basis of this study. Robson

(2002) argues that critical realism permits a new integration to what are usually referred to as objectivist and subjectivist approaches in social theory.

The different theoretical perspectives considered to build the theoretical framework for this study were the sociogenetic theories, of socio-cultural and social cognitive and cognitive information processing theory. The argument that sustains the adopted approach is based on the fact that; competence in physics problem solving is a product of the triggered generative mechanism in given contexts. The acquired competence occurs on two planes, external and internal. Table 2.1 summarises the different theoretical perspectives, their generative mechanisms and strategies to trigger these mechanisms.

	Theory and proponents	**Generative mechanisms**	**Strategy and context**
1.	**Sociocultural** Vygotsky (1978), Van der Veer and Valsiner (1991) and Rogoff (1990)	• Social interaction (Vygotsky, 1978) • Private speech as a mechanism for turning shared knowledge into personal knowledge –internalisation appropriation (Berk & Spuhl, 1995; Bivens & Berk, 1990) • Cognitive Apprenticeship (Rogoff, 1990; Collins, Brown & Newman, 1989) • Self-regulation • Argumentation (Miller, 1987)	• Use of cognitive tools (strategies, models, graphs, equations, symbols). • Guided participation in ZPD. • Self-directed speech. • Social interaction through collaborative group problem-solving. • Peer mentoring, tutoring and feedback. • Reciprocal teaching. • Scaffolding (Brunner, Wood & Ross, 1976).
2.	**Social cognitive** Bandura (1997), Pintrich and Schunk (2002) and Schunk & Zimmerman	• Self-efficacy as the mechanism of agency: • Agency determines regulation of action and competences through micro-mechanisms of self-organising, self-regulation, self-reflection and being proactive • Self-regulation also controls	• Collaborative cooperative group problem solving. • Modelling through cognitive apprenticeship. • Modelling and observation. • Scaffolding. • Sustained practice for enactive mastery on

	(2006)	self-efficacy	application of strategies. • Monitored enactments with constructive feedback. • Provide positive, competence-promoting feedback. • Promote mastery on challenging tasks through challenging tasks within the student’s ability**.**
		• Anticipative mechanism of forethought; self-regulatory mechanism for goal setting, planning, outcome expectancies and causal attributions based on past outcomes.	
		• Concept matching for transition from conceptions to skilled action	
		Metacognition	• Self-setting of goals with ways to evaluate. • Development of self-instructions during problem-solving. • Self-monitoring to increase students’ attention towards their work (their time on task) and the number of assignments they complete. • Self-evaluation by developing appropriate standards, goals and objective techniques to observe their own progress in problem-solving.
•	**Information processing theories**	***A.*** **Macro-mechanisms** *1.* Schema construction and integration *2.* Transfer *3.* Metacognition ***B.*** **Micro-mechanisms** *i.* Attention *ii.* Perception *iii.* Encoding	• Embedding conceptual models in problem solving. • Structure maps. • Question prompts on retrieval and metacognition. • Text editing. • Analogical encoding. • Problem classification.

		iv. Storage *v.* Retrieval through activation spreading *vi.* Motivation *vii.* Cognitive load reduction	- Explicit teaching of metacognitive strategies. - Creation of external records during problem solving.

Table 2.1: Theoretical perspectives, generative mechanisms and intervention strategies

2.5 Statement of the problem

Problem solving occupies a pivotal role as one of the key skills in line with all GCE A-level assessment objectives. In addition, problem solving is a viewed as a summative assessment tool for knowledge, skills and understanding of physics concepts. However, the traditional approach of implicit teaching of problem-solving strategies has resulted in a shallow approach to problem solving by the students. With this approach, good problem-solving strategies are modelled for students by the teacher with less emphasis on explaining the approach chosen. With the surface approach, students move from the unknowns and matching the given quantities with an equation. There is very limited structural analysis of a given problem as an initial stage in solving the problem.

This study aimed to develop a deep approach to problem solving, through collaboration, to trigger the use of explicitly taught strategies – cognitive and metacognitive. Through this approach, students were explicitly taught problem-solving strategies to develop both metacognitive and cognitive proficiency. These strategies, aimed at critically engaging with the problem, were modelled by the teacher through cognitive apprenticeship and applied by the students during collaborative group problem sessions throughout the study period.

2.6 Research aims

This study explored the impact of the explicit teaching of problem-solving strategies to a group of 10 students in the AS course in an inner London academy. Data collection was undertaken in the period March 2013 to October 2013.

The aims of this study were to:

1. assess how students approach physics problem solving when problem-solving strategies are implicitly taught within the curriculum;
2. explore the generative mechanisms triggered by an intervention which involves the explicit teaching of problem-solving strategies through collaborative group problem solving;
3. analyse the impact of the intervention on students’ approaches to physics problem solving.

3.0 RESEARCH METHODOLOGY

The study sought answers to the following research questions:

1. How do A-Level physics students in an inner London comprehensive school approach physics problem solving?
2. What generative mechanisms are triggered to bring about a change in the approach to physics problem solving (PPS) by the explicit teaching of strategies and how do these generative mechanisms compare with the existing approach?

The following section explores the philosophical underpinnings of critical realism that guided this study.

3.1 A critical realist methodology

From a critical realist perspective, the object of this study – the physics problem-solving process, within an urban multicultural school in an area of high deprivation – is a process driven or constrained by certain generative causal mechanisms operating in open systems, subject to the different contexts existing within and outside the classroom walls. A tenet of critical realism in social research is to treat reasons as causes. The intentionality of praxis to transform the world demonstrates humans' ability to change the world. The reasons people have for doing things are analogous to the causal structures of nature (Bhaskar, 1978); they belong to the causal order, cohabit and interact with other causes in the open system (Collier, 1994).

The underlying assumption is that causal powers reside not with individuals but their interactions with social relations and organisational structures. They view is that mechanisms are about people's choices and the capacities they derive from group membership. The reality, success and failure of the physics problem-solving process, occurs in different strata with different causal mechanisms generated by different contexts.

Questions that have to be answered include: What is it with the designed strategy (PPS) that would trigger a change in approach to problem solving? Does the strategy provide a means for students to change their approach to problem-solving? The final objective is to demonstrate how the intervention strategy outputs follow from students' 'choices' and their capacities (cognitive, metacognitive, cognitive and collaborative resources). The argument to change the approach of teaching is rooted in the argument that; causal mechanisms and their effects are not fixed, but contingent. It is their contextual conditioning which turns or fails to turn causal potential into a causal outcome. Like any other programme, introducing an intervention strategy wrestles with prevailing contextual conditions which will set limits on the efficacy of the intervention strategy (Pawson & Tilley, 1997).

The initial stage of this study, mostly speculative and based on established theory, involved a literature review to determine the causal mechanisms that enable or disable successful physics problem-solving and the contexts in which these operate within the social system. This fits in with the initial exploratory phase of an action research study methodology. From the chosen philosophical perspective, critical realism, an action research study is viewed as a social programme (Pawson & Tilley 1997; Danermark et al., 2002; Somekh & Lewin, 2012).

From a critical realist vantage point, the objective of the study was to establish theory-laden facts about 'what is it about the problem-solving strategy that makes it work' not whether it works or not. The initial context for this study involved a 'free fall' in GCE A level physics pass rate to the extent that there was no A2 group. There was little evidence of a culture of independent study and a clear absence of self-regulatory practices like use of learner diaries to plan the weekly tasks to enhance retention and transfer of physics concepts. Problem solving was viewed as a means to an end, to pass the examinations. A desired context which would trigger the firing of the mechanisms that trigger competence in problem solving required of an intervention strategy to trigger a shift to a culture of self-responsibility. The aim was to develop self-regulation strategies, build an appreciation for the impact of collaborative group work and foster an understanding that problem solving is a life-long transferrable skill that has to be nurtured and developed throughout the passage of time. This list is not exhaustive.

Interventions within the learning process are considered as occurring in open systems with a 'morphogenic' character (Bhaskar, 1979; Archer, 1995). All social systems change and agency for people in social systems can be enabled. The balance of causal mechanisms, contexts and regularities which sustain the social order is prone to perpetual and self-generalised reshaping (Pawson & Tilley, 1997). For change to be evaluated, the initial point is to identify the regularity (R1) that is deemed to represent the social problem and the mechanism (M1) that sustains it within a given context (C1) at a time T1. The quest is to shift the behaviour to a more acceptable level (R2) by introducing a mechanism (M2) within the same context up to a time T2. The change in rates (R2-R1) will constitute the outcome (O) (Pawson & Tilley, 1997).

With a critical realist grounded study of social phenomena, it is not theory construction that matters but understanding what exists and what do participants do, to whom and with whom do they do it. The long-standing debate has always been the degree to which individuals have free will or are constrained by circumstances, i.e. structures. Whether or not individuals have agency, the capacity of individuals to take and exercise control in given social contexts is determined by the social structures within which they live at that particular socio-historic moment (Somekh & Lewin, 2012). Structure enables and constrains action; human action reproduces or transforms structure; and both agents and structures have causal powers (Somekh & Lewin, 2012). People as agents produce and recreate structures which later enable or constrain the action of agents (Bhaskar, 1979). For agents to be causally efficacious they must know about the mechanisms they want to trigger, block, subvert or replace to make appropriate causal interventions, for without causality any concept of responsibility and agency is meaningless (Sayer, 2008). The morphogenetic sequence', on the interdependence of structure and agency, views structure and agents as operating on different timescales. The view is that, at any particular moment, antecedently existing structures constrain and enable agents, whose interactions produce intended and unintended consequences, which leads to structural elaboration and the reproduction or transformation of the initial structure.

A realist study is context-mechanism driven for the purpose of transferrable lessons rather than generalisability as with positivist research. The study should strive to explore the contextual constrains for the operation or suppression of the change mechanisms. A contextual variation will trigger a corresponding variation in the effectiveness of causal mechanism and a consequential variation in patterns of outcomes. The explanation for observed socially significant regularity (R) should posit the underlying mechanism (M) which generates the regularity, making clear the role of the interplay between structure and agency. How the underlying mechanisms are contingent and conditional within the given context (C) should be investigated. The explanandum (what to be explained) and explanans (series of statements) are related thus: *regularity = mechanism + context*. Justifying the success of a strategy is grounded on how the identified mechanism (M) works in the given context (C) to produce the regularity (R) (Pawson & Tilley, 1997).

3.2 The critical realist grounded research study

This study sought to establish facts about 'What is it about the explicit teaching of problem-solving strategies that make it work? ´, not whether it works or not. Envisaging physics problem solving as a product of the active involvement of students in the proposed and agreed intervention programme, an action research with a critical realist perspective was chosen. From this perspective, the powers for a shift towards competence physics problem solving (PPS) reside not within the individuals but their interactions with social relations and organisational structures.

PPS as an educational process within an urban multicultural school situated in an area of high deprivation is viewed as a process driven or constrained by certain generative causal mechanisms in open systems. These mechanisms are subject to the different contexts that exist within and outside the classroom walls. The reality, success and failure of the physics problem-solving process occur in different strata with different causal mechanisms generated by different contexts. In this case, the study focused on those mechanisms that could be triggered within the learning context. It can be argued that introducing an intervention strategy wrestles with prevailing contextual conditions, hence limiting the efficacy of the intervention strategy (Pawson & Tilley, 1997). Grounding this study in the context of the students who are the focus of the study improves the internal validity of this approach (Pawson & Tilley, 1997; Flick, 2002).

For the two cycles of this study, data were collected at the beginning of the intervention as entry data, after the first intervention and at the end of the second intervention, as exit data.

3.3 The context and the participants

I joined the school where this study was conducted in September 2012 as the only specialist physics teacher. The GCE A level physics pass rate had decreased drastically; consequently, the GCE A2 course had been discontinued at the beginning of the academic year, September 2012. Within the learning process, there was no evidence of collaborative work even when students were asked to work in pairs or groups of threes. Problem solving was viewed as a means to an end, to pass the exams and when it occurred, any numerical data were substituted into the nearest equation that looked familiar! There was little evidence of a culture of independent study and a clear absence of self-regulatory practices like use of learner diaries.

The participants initially consisted of the ten advanced subsidiary (AS) students (8 boys and 2 girls) in the OCR-A GCE physics course. The predicted grades for this group ranged from U to B. Initially the whole group participated and later only four students, purposively selected, took part in the study. The GCE AS courses covers Mechanics and Electricity.

In March 2013, when the intervention project was launched, one student withdrew his consent. Of the remaining nine students, five decided not to continue after AS at the end of the academic year, July 2013. However, the intervention strategy involved all the students in the physics class but data collection was focused on the four remaining students who later proceeded to A2 physics.

3.4 Ethical issues

Data generation and collection about people, with people situated within a larger learning context, demands ethical considerations that go beyond abiding by guidelines such as those provided by BERA (2014). The ongoing nature of this study offered many possibilities for the emergence of ethical dilemmas during the intervention and later when disseminating the findings. Some of these challenges included maintaining a balance between my positions both as a teacher and as a researcher, creating a shift in power relations to a state that would foster collective effort and a feeling of empowerment on the part of the students.

Other challenges emanated from the sudden changes within my professional context and some students withdrawing from the study. In addition, the embedded nature of the intervention process created a blurred line as to what constituted research and what constituted learning within the designated lesson time especially with the students who later withdrew from the study. These students had to participate in the collaborative group activities as these activities were part of the learning process. However, the students who had withdrawn were not video-recorded. Maintaining the desired balance between my roles as a teacher and a researcher was not easy to achieve but I had a constant awareness of the power relations that existed between me, the school authorities and the participating students.

Consent was sought from the school authorities, the participating learners and their parents or guardians. I made it clear to the participants and the school administration that students' academic needs were not put in jeopardy for the sake of this study, indeed the idea was to enhance student learning. I outlined the purpose of the study to the participants before the informed consent forms were signed. Participants were provided with the research framework and aspects that the research intended to cover, to ensure that they made an informed decision as well as making it clear what I needed them to do. It was explicitly made clear to the participants that there would be video recordings during sessions and that these would be destroyed as soon as the data analysis process was completed. Teachers and technicians in the department were informed of the study. Participants were informed from the start that they retained the freedom to opt out of the project at any time without any fear of reprisals.

Most of the interventions took place during lesson time and the students consented to any extra time that was required to finish sessions after school. Sessions for recording were negotiated and dates moved to accommodate those who were otherwise unavailable. In addition, students were involved in the decision-making process, initial data analysis and feedback with view to evaluating and improving the next cycle of intervention. The findings from the initial analysis were shared with the students and how the explicit teaching of the strategies including heuristics would be embedded with the learning process. This will be explained in the section for initial data analysis. Constant feedback was provided to the participants on the progress of the study and their personal progress. In addition to complying with ethical guidelines, clarifying and discussing the findings with the participants also increases the internal validity of the study (Rudestam & Newton, 2007).

Confidentiality and anonymity can only be guaranteed where this is possible and I was honest as to where it was not. In an effort to guarantee anonymity during the action research, the final analysed data use pseudonyms. Participants had access to any data regarding themselves (BERA, 2014 section 27). The school was informed that anonymity might not be possible in a case where the study is published under my name and so becomes available in the public domain as people who know me and know where I taught at the time of the study will therefore know the name of the school, even though a pseudonym is used. The initial data gathering phase began after the approval of the study by the school and the university ethics committee and the signing of the consent forms by parents and students.

With regards to the collected data in the form of videos and answer scripts, the participants were informed that once an exhaustive data analysis was completed, the data would be destroyed. There exists an ethical dilemma, not destroying rich data that could be useful for further studies on problem solving in a similar context or upholding the promise to the participants? My argument is that; clarifying to the participants that’s their recorded data and answer scripts would be destroyed after the exhaustive analysis contributed to the decision to participate and it would be ethically correct to destroy the collected data otherwise the data would have been collected by deception. It is important to reiterate that a time frame or set date for the destruction was not set.

3.5 The intervention phases

The study consisted of three phases, one exploratory and two interventions. These phases are discussed in detail in the following sections.

3.5.1 The pre-intervention phase

The pre-intervention phase consisted of exploring and describing how students approach PPS through observations of individual and group problem-solving sessions and using existing data. The impact of problem-solving strategies in various contexts was also explored by reviewing existing academic literature on PPS to link practice to theory. Data to examine the PPS process within the context were gathered through external examination answer scripts, video recordings of individual and collaborative group problem-solving sessions. Questionnaires on self-efficacy in problem solving were initially used but discarded. Answers obtained with these questionnaires did not reflect the reality on the ground. Different frameworks were used to analyse the data for metacognitive and cognitive competences, and self-efficacy. The contexts and mechanisms which sustained the existing situation of poor problem solving were also probed.

In response to the findings of this phase, the intervention strategy for PPS was formulated to develop cognitive and metacognitive competencies (internal mechanisms) through collaborative group problem solving, embedded within the physics curriculum. The theoretical framework map (Figure 3.1) shows the targeted mechanisms.

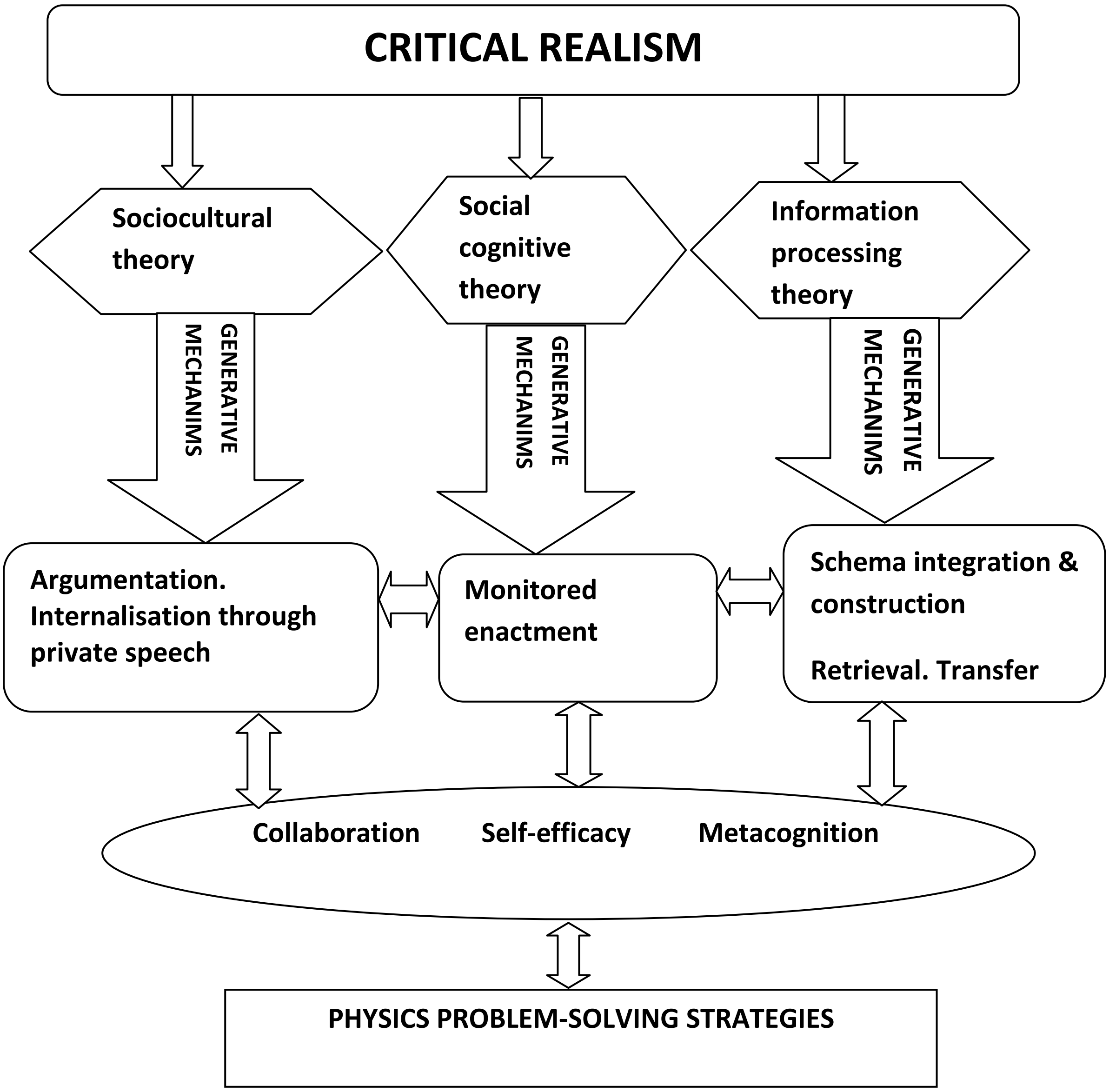


Figure 3.1: Summary of the intervention framework

3.5.2 The first intervention phase

This first cycle of the action research, March 2013 – May 2013, involved the embedding of the proposed strategy within the curriculum. The start of the intervention coincided with the release of the January 2013 external examination results. Whole-class discussions on the results followed and students unanimously agreed that they lacked strategies to deal with physics problems. After the initial data analysis, a new strategy was proposed, with a collaborative approach.

The nine students divided themselves into cooperative groups, later collaborative ones. Through cognitive apprenticeships and modelling, the students were taught problem-solving strategies including heuristics. Initially, students assumed fixed roles like manager, checker, critic and scribe and group functioning was evaluated at the end of each session. Work was peer-assessed and group members were encouraged to present and defend their approaches to problem solving. Other group members would then assess the presented work using success criteria reflecting the implemented strategy.

Table 3.1 summarises the different theoretical perspectives, their generative mechanisms as per the literature reviewed, the contexts and strategies to trigger these mechanisms. This was an attempt at establishing the possible context-mechanism-output configurations in PPS. However, the complexity of the human thinking process makes it impossible to isolate with certainty what mechanism is being triggered. Different contexts included opportunities for collaborative work through collaborative group problem solving (CGPS), feedback sessions with self-evaluations.

Theory and proponents	**Generative mechanisms**	**Strategy and context**
Sociocultural Vygotsky (1978), Van der Veer & Rogoff (1990) and Valsiner (1991)	***1.*** Social interaction (Vygotsky, 1978) ***2.*** Private speech as a mechanism for turning shared knowledge into personal knowledge –internalisation appropriation (Bivens & Berk, 1990; Berk & Spuhl, 1995) ***3.*** Cognitive Apprenticeship (Collins, Brown & Newman, 1989; Rogoff, 1990) ***4.*** Self-regulation ***5.*** Argumentation (Miller, 1987)	***1.*** Use of cognitive tools (strategies). ***2.*** Guided participation in ZPD. ***3.*** Self-directed speech during problem solving. ***4.*** Social interaction through CGPS sessions. ***5.*** Peer mentoring, tutoring and feedback. ***6.*** Reciprocal teaching. ***7.*** Scaffolding (Brunner, Wood & Ross, 1976).

Social cognitive Bandura (1997), Pintrich and Schunk (1991) and Zimmerman (2006)	***1.*** Self-efficacy as the mechanism of agency ***2.*** Self-organising, self-regulation, self-reflection and being proactive ***3.*** Anticipative mechanism of forethought; self-regulatory mechanism for goal setting, planning, outcome expectancies and causal attributions based on past outcomes ***4.*** Concept matching for transition from conceptions to skilled action ***5.*** Metacognition	***1.*** CGPS sessions ***2.*** Modelling through cognitive apprenticeship. ***3.*** Scaffolding ***4.*** Sustained practice for enactive mastery on application of strategies **b**y using challenging tasks which can only be solved by the whole group not one student ***5.*** Monitored enactments with constructive feedback aimed at promoting competence ***6.*** Self-setting of goals with ways to evaluate. ***7.*** Development of self instructions during problem-solving ***8.*** Self-monitoring to increase students' attention towards their work (their time on task) and the number of assignments they complete ***9.*** Self-evaluation by developing appropriate standards, goals and objective techniques to observe their own progress in problem-solving
Information processing theories	**1.** Schema construction and integration ***2.*** Transfer ***3.*** Retrieval **Micromechanisms** ***i.*** Attention ***ii.*** Perception ***iii.*** Encoding ***iv.*** Storage ***v.*** Retrieval through activation spreading ***vi.*** Cognitive load reduction	***1.*** Embedding conceptual models in problem solving. ***2.*** Structure maps ***3.*** Question prompts on retrieval and metacognition ***4.*** Text editing ***5.*** Analogical encoding ***6.*** Problem classification ***7.*** Explicit teaching of metacognitive strategies ***8.*** Creation of external records during problem solving

Table 3.1: Theoretical perspectives, generative mechanisms and the strategies

Data were collected after six sessions, analysed and the context-mechanisms-outcomes configurations identified. Evaluation of the first intervention outcome was undertaken to identify any changes and solicit feedback from the group. In the second intervention phase, the focus shifted to four students who had a high likelihood of proceeding to A2 physics. Students requested a shift from the context-rich problems to exam-type problems and a simplification of the adapted Docktor and Heller framework (Docktor & Heller, 2009). The outcome was a one page cognitive metacognitive prompt sheet to refer to during problem solving (appendix 4).

3.5.3 The second intervention: exit phase

With the changes effected, the focus in this phase was on further developing the individual and group competencies based on the entry data and from the first intervention. During this phase (June 2013 – October 2013) students were able to review and compare their performance in both the January 2013 and June 2013 GCE AS physics results. Students swapped their exam scripts and discussed what each should have done using the learnt strategies. For example, one student left many problems unsolved and lost about 27 marks due to poor time management. The group agreed to give him the role of manager in most CGPS sessions. The group asked for more sessions and offered to have one Friday afternoon every fortnight for CGPS sessions. Data were collected after about 12 sessions and analysed as exit data.

A timeline to summarise these different the stages in this study is shown (table 3.2)

PHASE 1: Stage 1: Planning and Literature Review **Period:** September 2012 – December 2012	
Actions	A traditional approach to teaching GCE-A physics as advised in schemes of work is adopted. A study of the learning environment and prevailing context. Analysis of available student and school data on physics learning. Finalising the area of focus for the research project. Prepare intervention materials, including adapting some materials from other research projects. Drafting of consent letters. Developing of the action plan.
PHASE 1: Stage 2: Planning and Literature Review **Period:** January – February 2013	
Actions	Submission of research proposal and ethics form to the university. Students sit for January external examinations. Research project approved by school and university. Students and parents sign consent forms. Meeting with school authorities to brief them on the project. Meeting with the students to discuss on how the project will be conducted. Initial video and written data collection, including preliminary analysis of entry data. Administering of self-efficacy questionnaire.
PHASE 2: First intervention: A shift in the physics problem-solving pedagogy **Period:** March – May 2013 **Number of sessions**: 6	
Actions	Practise with video and audio recording equipment. Deployment of formulated strategies during the learning process. Video data collection. Continuous feedback between the participants and teacher. Whole group evaluation and feedback to teacher.

	Reformulation of strategy action plan. Students sit for the June external examination (June 2013).
PHASE 3: Second intervention: A shift from a cooperative to a collaborative approach **Period:** June – October 2013 **Number of sessions**: 12	
Actions	Collaborative Group Problem Solving (CGPS). Targeted intervention at individual and group level using data from first intervention. Analysis of external examination scripts. Further review of the intervention strategy. Collection of exit data and preliminary data analysis. Feedback to group. End of the intervention process.

Table 3.2: A time-line of the research project.

3.6 The qualitative methodological approach

A qualitative methodology was decided upon as a suitable approach to attend to the research questions of this study. Despite facing heavy criticism from positivists, Denzin and Lincoln (1994) argue that imposing schemes from the positivist world on the social world is incompatible with the multiple worlds we live in, that are characterised by fragmentable experiences. Hammersley (2008) argues for qualitative research to demonstrate an understanding of the researched people's views and recognition of the extent to which social life is contingent, and even an emergent process (Hammersley, 2008). In addressing the criticism of quantitative inquiry, qualitative research must address issues of measurement, causal analysis and generalisation. In explaining causal links, an effective way of determining 'what explains what' must be found (Hammersley, 2008).

The quality of a study, from a qualitative perspective, is concerned with the soundness or 'trustworthiness' of findings of the study, warranted by the methods that are employed (Mertens, 2010). The term 'trustworthiness of the research' is used in distinction to the terms 'reliability' and 'validity' used in quantitative research (Rudestam & Newton, 2007). An indicator for the quality of qualitative research is the approach which must be evidenced by documentation that shows how the research was conducted and how the data were analysed and the interpretation undertaken (Mertens, 2010). Guba and Lincoln (1989) equate credibility with internal validity, transferability with external validity, dependability with reliability, and conformability with objectivity.

The systematic recording and coding of the data was executed in such a way that another person can understand the themes and reach similar conclusions, ensuring reliability/dependability in qualitative research (Rudestam & Newton, 2007). Internal validity deals with establishing the 'trustworthiness' of reported observations, interpretations and generalisations. The focus is on the extent to which the observations are grounded in those of the participants who are the object of the study. Triangulation must be viewed in its original context, argues Hammersley (2008), to counter threats to validity of one method which has divergent challenges to its validity. However, it can also be viewed as an approach to enriching the data and completing knowledge (Flick, 1998). This study used three methods for data collection and for data analysis, thematic coding was used to verify the qualitative content analysis framework used for coding the videos.

The Guba and Lincoln framework for quality of qualitative research was adopted (Guba & Lincoln, 1989) and a summary of how this study met the criteria is shown in Table 3.3.

Quality	**Action taken**	**What was done during the research**
Credibility	Prolonged and persistent engagement	The intervention was embedded within the curriculum; it started in March 2013 and finished in October 2013. Observations were carried out up to the external examination time (May 2013) and at the beginning of the GCE A2 course (September – October 2013).
	Member checks	Recorded videos were used in subsequent lessons with students judging their progress against given success criteria for competent problem solving. Students had to verify the teacher´s initial analysis. This involved whole group discussions on progress with peers assessing each other´s

		work.
	Progressive subjectivity	Progressive subjectivity involves the researcher conducting a close analysis of the evolving data constructions over time to ascertain whether the subjective assertions do not change over time and also to ensure that the researcher does not only see what they only want to see (Guba & Lincoln, 1989). This action research study had two cycles. The intervention in the second cycle depended on the analysis of the data and observations from the first cycle and feedback from participants. For example, students requested for; more sessions after school, a condensed version of the heuristics and a focus on the typical examination problems rather than the context-rich problems initially used.
	Triangulation	Three types of data collection probing for the same constructs were used and convergence or non-convergence of data from exam scripts was checked against protocols produced during individual and collaborative PPS sessions. The qualitative content analysis (QCA) frameworks were verified using a thematic analysis approach.
Transferability	Thick description and multiple cases	Whilst the burden of transferability lies with the reader (Mertens, 2010), sufficient detail on how the methods for data collection were deployed and the frameworks for data analysis were used is included in the study for the four students. The context of the study is well detailed to capture the complexity of the study. The four students provide different perspectives on the possible scenarios of the study.
Dependability	Dependability audit	The collection, processing and analysis of data at various stages of the study allows for easy tracking of progress throughout the study. The protocols for various PPS sessions

		are included as part of the study at every stage for the four cases.
Confirmability		The sources of the data are provided and the theoretical frameworks used in the processing and analysis made explicit. The video transcriptions are available as part of the work so external reviewers can independently judge the extent which conclusions are supported by the data.

Table 3.3: Criteria for credibility of qualitative research (Guba and Lincoln (1989)

3.6.1 Data collection methods

To answer the research questions, data about specific situations and events were collected and analysed to give a clearer picture of the causal processes. Two different data collection methods were used: examination scripts; and protocols from video records of problem-solving sessions (individual and group). To explore the impact of the intervention strategy through collaboration, video data on collaborative group problem solving were collected. In addition, students were video-recorded during individual problem-solving sessions. An analysis of the entry data and the subsequent two cycles allowed me to identify how the possible mechanisms triggered by the intervention are distributed within and between intervention contexts.

The two methods were chosen on the grounds that the strength of each provides a different perspective on the process of problem solving. This triangulation through data collection methods reduces the risk that the data collected only reflect the systematic biases of one method (Maxwell, 2012). Whilst observation of the physics problem-solving process through video recording allows for a fine-grained analysis of the process it does not provide evidence of how students solve problems as individuals under certain contexts like examinations. Examination scripts, though not making the processes apparent, provide a clearer picture of the outcomes of the intervention process in the target contexts, external examinations.

An attempt to use questionnaires to gauge self-efficacy was discontinued. The responses on the rating scales were inconsistent with the reality I knew as the physics teacher. Initially an adapted questionnaire for measuring students' self-efficacy (Fencl & Scheel, 2004).In measuring beliefs of personal efficacy, Bandura (2006) suggests anonymity as one the safeguards to minimise any potential motivational effects of self-assessment. Self-efficacy judgments are to be recorded privately without personal identification to reduce social evaluative concerns. However, this presented problems when individual self-efficacy was required as part of the entry data before the intervention.

Despite the advantage of being easy to apply, questionnaires rely on honesty of participants. When the questionnaires were applied some students rated themselves highly on all items, including reverse items. Some even gave a rating rated where there were no items to respond to. One student rated himself above 80% on all the items. However when presented with physics problems soon after, the student couldn't answer a basic problem that only required recalling a simple formula and substituting the data.

Many possibilities exist for this behaviour. Students might have wanted to create an image of 'cool' amongst their peers. They might have lacked an accurate introspective ability to provide accurate responses despite their best efforts. From literature reviewed, the validity of using questionnaires is always questioned in such circumstances. Richardson (2004) and Perry and Winne (2006) argue that learners may not be able to accurately report what they generally do or what they have done in finishing an assignment. Additionally, questionnaires may measure learners' perceptions rather than the strategies actually performed. Veenman (2005, 2011) assumes that self-reports do not measure the actual activities performed, rather, they may assess knowledge of those activities. Furthermore, such knowledge does not to imply that learners will actually perform those activities. In the illustrated example, the student overrated his confidence because he was sitting with his peers.

These arguments buttress the observations and despite the immense effort and time invested in drafting and adapting the questionnaire I decided that for such a small group, this approach to data collection would pose some serious challenges to the validity of my research findings. The use of the questionnaire was discontinued (Appendix 11).

3.6.2 Data from examination scripts

Very little literature currently exists on analysis of physics examination scripts with a focus on processes. Reports from chief examiners focus more on the outcomes of the exam process rather than the possible processes that lead to success in PPS. Answer scripts provide evidence of the product cognitive skills, the ‘visible footprints’ of the PPS process, but do not shed light on how the process unfolded, including the metacognitive processes.

In addition, not everything is verbalised during group or individual PPS sessions and scripts provide a clue as to the end product of such verbalisations and other processes that were not captured through the recording process. Viewed as text, scripts give information on the background scenario for the subsequent analysis (Silverman, 2011). They provide a view of the bigger picture on attainment and performance under actual examination conditions. From these written examination scripts, attainment can be evaluated and the cognitive steps inferred from the written solutions.

Whilst the validity of the analytical framework proposed can be subject to debate, the content validity of the problems on the answer scripts was deemed high based on the fact that these problems are externally assessed, conforming to desired national standards. The analytical framework assesses the cognitive competences consistent with an expert approach to effective problem solving. The analysis was inferential to the possible cognitive processes that could have or should have occurred during PPS for a successful solution (Docktor, 2009). For the script analysis, three categories were used: focus the problem, plan the solution and execute. The initial data analysis revealed these categorise on written problem solutions.

3.6.3 Videos for the individual and collaborative PPS sessions

For recording the PPS session for individual students, the concurrent verbalisation (think aloud) approach was adopted (Simon & Newell, 1972, 1993). This method requires the solver to verbalise the inner language of the short term memory activity without the student editing, explaining or theorising the verbalisation in order to minimise the cognitive demand working memory. This ensures the veridicality of the heeded information and improves the validity of the data produced (Taylor & Dionne, 2000). Ericson and Simon (1993) define veridicality of verbalisations as those utterances closely related to the thought processes. This additional cognitive activity changes the sequence of mediating thoughts.

To reduce cognitive load, level 2 verbalisations were chosen during problem solving. These are verbalisations that do not require new information to be brought in the participant's focus but do require recoding. This level of verbalisation only explicates or labels information that is held in a compressed format in the STM (Ericsson & Simon, 1993). To optimise reporting directly from the STM and maximise the richness of the data, only tasks that were likely to require verbal encoding, deliberate, conscious and goal-directed cognitive activity should be used, instead of simple or familiar tasks (Ericsson & Simon, 1993; Kellogg, 1987). The task problems were considered novel and moderately difficult so as to elicit conscious processing (Afflerbach & Johnson, 1984; Ericsson & Simon, 1993; Schifrin & Schneider, 1977) but not so difficult as to stymie reporting (White, 1980).

The concurrent verbalisation approach to data collection is limited in that it cannot reveal everything going on in the learner's mind during problem solving. Acknowledging the shortcomings of the concurrent think aloud approach, Afflerbach and Johnson (1984) and Ericsson and Simon (1993) point out that only heeded traces of thinking will be verbalised and, consequently, automated or parallel processing cannot be reliably reported. Secondly, overt verbalisation of the thoughts means that the learner must engage in additional cognitive processes to generate the thoughts corresponding to the required explanations and descriptions, which results in an increase on the cognitive load.

However, despite these challenges to its validity the method reveals much more than is ordinarily apparent Reif (2008). This approach has been used in investigating mathematics problem solving (Schoenfeld, 1985; Armour-Thomas et al, 1992; Yeap, 1998) and general problem solving (Swanson, 1990; Jausovec, 1994; DeGrave et al., 1996). Within physics problem solving this method has been widely used by researchers at different academic levels (Simon & Simon, 1978; Larkin et al., 1980; Chi et al., 1981; Amigues, 1988; Meijer et al., 2006; Abdullah, 2010). Among other proponents of this method, Schoenfeld (1985) and Goos et al. (2000) point out how the subjective analysis of the transcripts from verbal data has raised questions among many researchers about the validity of verbal methods. Goos et al. (2000) argue that verbal protocols, concurrent or retrospective, can provide useful information if they are treated as data from which information can be inferred by the researcher rather than by the participants. For this study, concurrent verbal reports were evaluated as the most powerful method to probe deeper into the deployment of executive decisions during the problem-solving process.

For CGPS sessions, evidence of the collaborative process and group efficacy, in addition to mechanisms that drive cognitive and metacognitive competences, was collected through video recordings. Schoenfeld (1985) argues that this approach reduces environmental pressure on the individual. In justifying their propositions and during arguments, group members explain their reasons for their actions. Schoenfeld (1985) further argues that working in dyads or groups provides a higher chance of verbalisation. However, the interaction from one partner may alter one member’s intended path of thinking. In addition to these disadvantages, interpersonal dynamics may shape the process with a more dominant character ‘taking over’ or a quiet one receding to the background. To reduce the impact of interpersonal dynamics, Heller and Hollabaugh (1992) suggest assigning group roles initially and with time these roles would be flexible. A group functioning evaluation form can be used in the early stages of the first intervention phase (Heller & Heller, 2009).

Chapter 4.0 DATA ANALYSIS: APPROACHES TO PHYSICS PROBLEM SOLVING

4.1 Introduction

This chapter aims to provide a thick description of how the data from the examination scripts and video recordings from problem-solving sessions were analysed to probe how physics problem solving evolved during the period of study. Two approaches were used: a top-down, qualitative content analysis (QCA) and a down-up, thematic analysis. Due to the different nature of the data, the extent to which these approaches were applied varied. Both QCA and thematic analysis were applied to the script data. However, only a QCA approach was used for the video data, with a thematic analysis approach used for verifying, expansion or reduction of the theoretically derived *a priori* categories in QCA. QCA is a data analysis approach where deductively derived theory and deductively driven data analysis work ‘down´ from pre-existing theoretical understandings (Glaser & Strauss, 1967; Bauer, 2000; Mayring 2001; Schreier, 2012). A *priori* established codes in the QCA framework provided a starting point for analysing cognitive, metacognitive and collaborative competencies. However, using a priori categories may restrict the extent to which the data ´speak` to the researcher (Schreier, 2012).

The choice of QCA as an analysis framework was based on three factors: (i) my limited training in qualitative data analysis, (ii) the time required to develop a new code (Boyatzis, 1998) and (iii) the systematic nature of content analysis which allowed me to fit the different sections of my data into pre-existing categories using the same sequence of steps (Schreier, 2012). As a reductive method, QCA allowed me to focus on the relevant material required to answer the research questions. The use of theory-based codes made implicit actions clear by theorising the data.

The first research question, *How do A-level physics students in an inner London comprehensive school approach physics problem solving?,* was addressed by analysing the January (OCR-A G481, 2014) external examination scripts and entry video on problem-solving (individual and collaborative). The analysis across and within cases throughout the study addressed the second research questions: What generative mechanisms are triggered to bring about a change in the approach to physics problem solving (PPS) by the explicit teaching of strategies and how do these generative mechanisms counteract the existing approach?

4.2 Exam script analysis

Deploying concept-driven (QCA) and data-driven (thematic analysis) strategies was geared to capturing in depth what is important about the data (Schreier, 2012). The Minnesota Rubric (Docktor & Heller, 2009) was used as the main QCA framework (see section 4.2.3) with sub categories derived from the script data and theory.

4.2.1 Exam script analysis: A thematic approach

Very little has been published on analysing students' performance in GCE-A level physics beyond the final answers on the answer scripts. A review of the examiners' reports reveals a focus on the final solution rather than the process that brings forth the solution. Physics problems used for the external examinations are different from the context-rich problems that are assessed using the Minnesota Rubric (Docktor, 2009). Consequently, a need to categorise these problems arose. The categories adopted were derived from the cognitive processes that might be involved in their solution. The different coding processes are described in the following sections.

Stage 1: Categorisation of script problems

Two main categories were adopted: qualitative (QL) and quantitative (QN). QL problems require descriptive writing, usually a scientific argument buttressed by causal explorations. QN problems are those that require calculations. Some of the problems were deemed only to require basic recall of concepts. However, even a 'define' problem does not simply imply direct retrieval of stored concepts. Table 4.1 summarises the codes for the problem categorisation adopted for this study. This categorisation was done for this study and reflects the nature of the problems in GCE-physics in the UK. Some problems can encompass more than one aspect of categorisation, e.g. QN-AN.

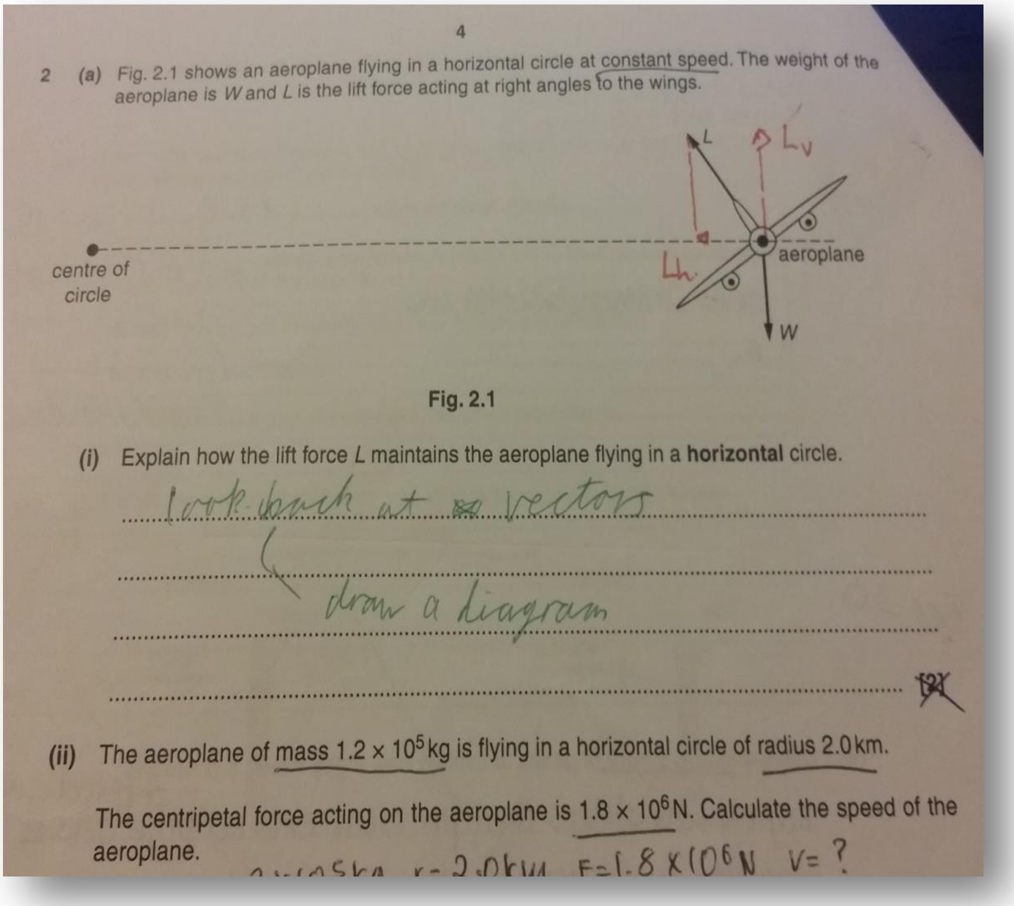
Category and code	**Description**	**Example**
Qualitative (**QL**)	Usually the answer is qualitative in nature and requires good quality written communication skills. Problems have the following command words: *define, state, explain.* The answer can solicit from basic recall to a detailed using scientific knowledge.	*State three assumptions of the kinetic model of gases.*
Quantitative (**QN**)	The problem requires mathematical procedures to progress to solution through manipulation of equations, graphs or other mathematical models.	*Calculate the radius of orbit of a geostationary satellite. The mass of the Earth is 6.0 x* 10^{24} *kg.*
Analytical (**AN**)	The problem requires an in-depth exploration of laws, principles, established scientific relations in the form of equations to explore causal links to a given scenario.	*Figure … shows an aeroplane flying in a horizontal circle at constant speed. The weight of the plane is W and L is the lift force acting at right angles to the wings.* *Explain how the lift force, L, maintains the aeroplane flying.*
Basic recall (**BR**)	The problem requires basic recall of scientific facts. Models or equations can also be used to answer these questions.	*Explain the term thermal equilibrium.*
Graphical or Visual Analysis	Interpretation or construction of a visual image depicting a given scientific scenario.	*Sketch the energy variations of the oscillator with*

(**GRA**)		*displacement.* *Label this graph K.*

Table 4.1: Codes for problem categorisation

Stage 2: Coding the problems

A key feature of GCE Physics problems (OCR-A) is their scaffolded structure. An example is given in Figure 4.1. While 2 (a) (i) requires a qualitative treatment based on the knowledge of vectors and centripetal force, 2 (a) (ii) requires further application of the knowledge but in a particular case. The close link between these two parts qualifies part (ii) to be categorised as a part question (part qn.), i.e. column 4 in Figure 4.2. This category was adopted for this study because of recognising the structural similarity of both parts of the problems and because the close link was viewed as part of the orientating phase.



4

2 (a) Fig. 2.1 shows an aeroplane flying in a horizontal circle at constant speed. The weight of the aeroplane is *W* and *L* is the lift force acting at right angles to the wings.

Fig. 2.1

(i) Explain how the lift force *L* maintains the aeroplane flying in a **horizontal** circle.

look back at ~~xx~~ vectors

draw a diagram

~~[2]~~

(ii) The aeroplane of mass 1.2×10^5 kg is flying in a horizontal circle of radius 2.0 km.

The centripetal force acting on the aeroplane is 1.8×10^6 N. Calculate the speed of the aeroplane.

$r = 2.0\,km$ $F = 1.8 \times 10^6\,N$ $V = ?$

Figure 4.1: Example of a scaffolded problem in GCE physics

The next step in this stage was to establish the themes from the script raw data. A theme, an outcome of coding, categorisation and analytic reflection, is an integrating relational statement that identifies what a unit of data is about and/what it means (Saldana, 2009; Bazeley, 2013). At a manifest level, a theme denotes observable phenomena and, at a latent level, underlying phenomena (Saldana, 2009). At a manifest level, actions were directly coded from the written data; however, the underlying cognitive processes are at a latent level.

Each complete written stage of the problem-solving process was categorised as a theme. In coding these raw data, the questions asked were: What is written on the script as part of the problem-solving stage? What do these written responses reflect of the problem-solving process? And what is not written that could have resulted in a complete solution? Table 4.2 illustrates this coding process (see table 4.1 for the abbreviations)

					Jamal	Sue	Mik	Nik
		Question type	**Part**	**Max Mark**				
1.		QL-AN	Y	2	No working. Correct answers (2/2)	Working shown with correct substitution (2/2)	No working. Correct answers (2/2)	No working. Correct answers (2/2)
2.	a	QL-BR	Y	2	No annotation / rough work (1/2)	Simple recall (2/2)	Simple recall (1/2)	Simple recall (2/2)
	b i	QN-CAL	Y	2	Equation → substitution. Cancelled initial answer (2/2)	Formula → substitution. **No link to context** (0/2)	Equations → substitution (2/2)	Equations → substitution (2/2)
	bii	QN-CAL	Y	2	Modelling → equation →substitution	Simple calculation. **No link to context** (0/2)	Model → calculations → answer. Evidence	**No modelling.** No attempt (0/2)
	biii	QL-AN	Y	2	**No analysis of context** (0/2)	Simple answer, no use of equation or diagram (0/2)	Correct answer (1/2)	Incorrect answer (0/2)
	b iv	QL-AN	Y	2	Answer written down. Correction done to answer (0/2)	Simple answer. **No analysis of context** (0/2)	Simple answer. **No analysis of context** (0/2)	Incorrect answer (0/2)
3.		QL-AN	Y	2	No working. Correct answers (2/2)	Working shown with correct substitution (2/2)	No working. Correct answers (2/2)	No working. Correct answers (2/2)
4.	a	QL-BR	Y	2	**No annotation / rough work** (1/2)	Simple recall (2/2)	Simple recall (1/2)	Simple recall (2/2)
	b i	QN-CAL	Y	2	Equation → substitution Cancelled initial answer (2/2)	Equation → substitution **No link to context**	Equation → substitution (2/2)	Equation → substitution (2/2)
	bii	QN-CAL	Y	2	Modelling →equation → substitution (2/2)	Simple calculation. **No link to context** (0/2)	Model → calculations → answer. Evidence	**No modelling.** No attempt (0/2)
	b. iii	QL-AN	Y	2	**No analysis of context** (0/1)	Simple answer, no use of equation or diagram (0/1)	Correct answer (1/1)	Incorrect answer (0/1)
	b iv	QL-AN	Y	2	Answer written down. Correction done to answer (0/1)	Simple answer. **No analysis of context** (0/1)	Simple answer. **No analysis of context** (0/1)	Incorrect answer (0/1)

Table 4.2: Extract of the initial data coding stage for the G481-2013 answer scripts

NB. *Comments in bold indicate what is absent that could have enhanced success in solving*

Stage 3: From themes to categories

The identified themes (table 4.3) were compared against each other for similarities and differences, and then grouped into categories (figure 4.4). For example, substituting data or changing subject is considered a form of mathematical manipulation or execution, mathematical manipulation or execution being the broader concepts. Consequently, substitution becomes one of the explanatory descriptors under mathematical manipulation or execution.

Themes that were found to be conceptually similar were aggregated and a category was designated, reflecting the reviewed literature. For example, good progress with QN-CALC problems and collapsing calculation stages made the `good mathematical procedures´ category.

	Themes	**Categories**
Jamal	• Good physics knowledge.	• Good specific application of physics concepts.
	• Accurate algebraic manipulations and calculations. • Evidence of good progression on problems involving calculations.	• Good mathematical procedures.
	• Skips a lot of steps but succeeds with most calculations, e.g. does not extract data or equations for definitions. • Use of basic heuristic: (*equations* → *substitution* → *solution*).	• Possession of basic heuristics on QN-CALC problems.
	• Loses marks mostly in QN-AN problems. • No evidence of analysis of scenario. • No modelling/diagram. • Relies on extensive writing for analytical problems.	• Inadequate problem-solving strategies for QL-AN problems.
	• Not checking problem comprehension.	• No metacognitive strategies
Sue	• Scores good marks with QN-CALC problems.	• Good mathematical procedures.
	• Use of the approach, *data* extraction → *equations* → *substitution* → *solution.*	• Possession of basic heuristics on QN-CALC problems.
	• Incorrect interpretation of problem state.	• Inadequate problem comprehension.

	• Loses marks mostly in analytical problems (no modelling through diagrams, planning solutions, exploration of causal relations). Not linking solutions to context.	• Lack of clear strategies on solving analytical problems.
	• Incorrect use of relations. • Analysis not based on clear physics concepts. • Incorrect equations. Incorrect diagram of forces. Incorrect analysis using model.	• Inadequate conceptual knowledge; incomplete problem schemata.

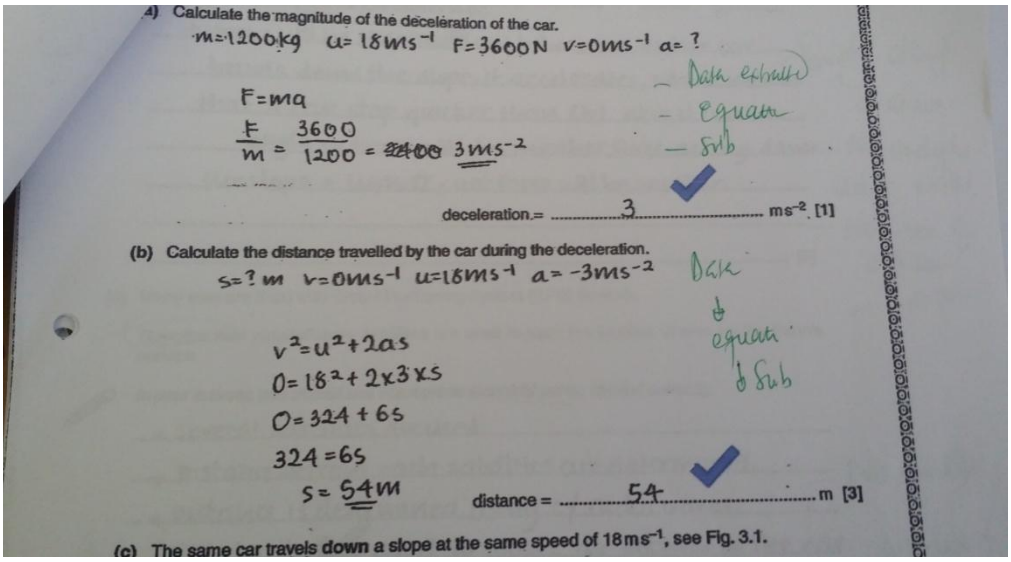
Table 4.3: From themes to categories

4.2.2 Findings from the G481 scripts and research question 1

The entry data sought to address the research question: *How do A-level physics students in an inner London comprehensive school approach physics problem-solving*?

The G481 thematic analysis revealed low scores for qualitative basic recall problems. Some of these problems formed the initial part of the scaffolding in a problem. With a solid physics conceptual understanding, these problems would require simple retrieval of concepts. To give an example, question 2 (a) required stating the difference and similarity between speed and velocity. This basic recall problem acted as a cue for higher level part questions 2b (i) - 2b (iv) that required students to calculate and explain. Failure to answer these QL-BR questions seems to have triggered a poor performance in subsequent parts of the problem. The first parts can be viewed as cues that help orientate the solver´s solution planning, helping to trigger the relevant schema. The data from all four cases showed no prior planning or use of models, diagrams or equations to help with the formulation of the solution.

For quantitative calculation problems (QN-CALC), a higher attainment compared to the basic qualitative is evidenced. Marks range from 11 to 18 out of the possible 20 marks. There is evidence of the deployment of the general calculations heuristic (data → equations → substitution → solution). An example of the application of the heuristic is shown in the sample of work in figure 4.2.



a) Calculate the magnitude of the deceleration of the car.

$m = 1200\,kg$ $u = 18\,ms^{-1}$ $F = 3600\,N$ $v = 0\,ms^{-1}$ $a = ?$

– Data extracted

$F = ma$

– equation

$\frac{F}{m} = \frac{3600}{1200} = \cancel{2400}\ 3\,ms^{-2}$

– sub

✓

deceleration = 3 ms^{-2} [1]

(b) Calculate the distance travelled by the car during the deceleration.

$s = ?\,m$ $v = 0\,ms^{-1}$ $u = 18\,ms^{-1}$ $a = -3\,ms^{-2}$

Data & equation & Sub

$v^2 = u^2 + 2as$

$0 = 18^2 + 2 \times 3 \times s$

$0 = 324 + 6s$

$324 = 6s$

$s = 54\,m$

✓

distance = 54 m [3]

(c) The same car travels down a slope at the same speed of 18 ms^{-1}, see Fig. 3.1.

Figure 4.2: Deployment of a basic heuristic

There is evidence in figure 4.2 of low comprehension of the problem requirements as shown by poor planning that is not linked to the actual context and inaccurate equations or specific application of physics concepts. In instances where there was no explicit data extraction, the final solution was incorrect. My claim is that explicitly extracting the data and writing down the specific equation would enable accurate monitoring during the substitution process. An example of the importance of this procedure is illustrated in figure 4.3. In this case, inspection of the data would have revealed the error in the computed perpendicular distance of the weight from the pivot and the error in standard form (46 x 10^2 m).

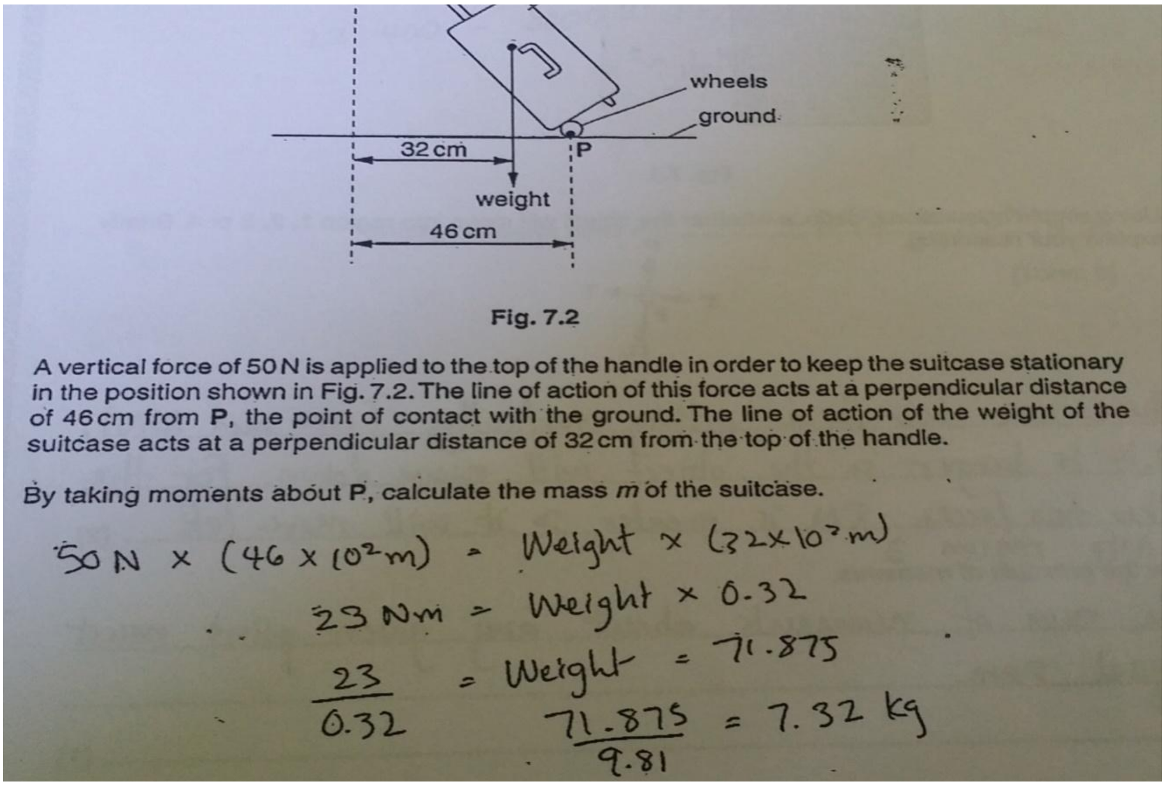


Fig. 7.2

A vertical force of 50 N is applied to the top of the handle in order to keep the suitcase stationary in the position shown in Fig. 7.2. The line of action of this force acts at a perpendicular distance of 46 cm from **P**, the point of contact with the ground. The line of action of the weight of the suitcase acts at a perpendicular distance of 32 cm from the top of the handle.

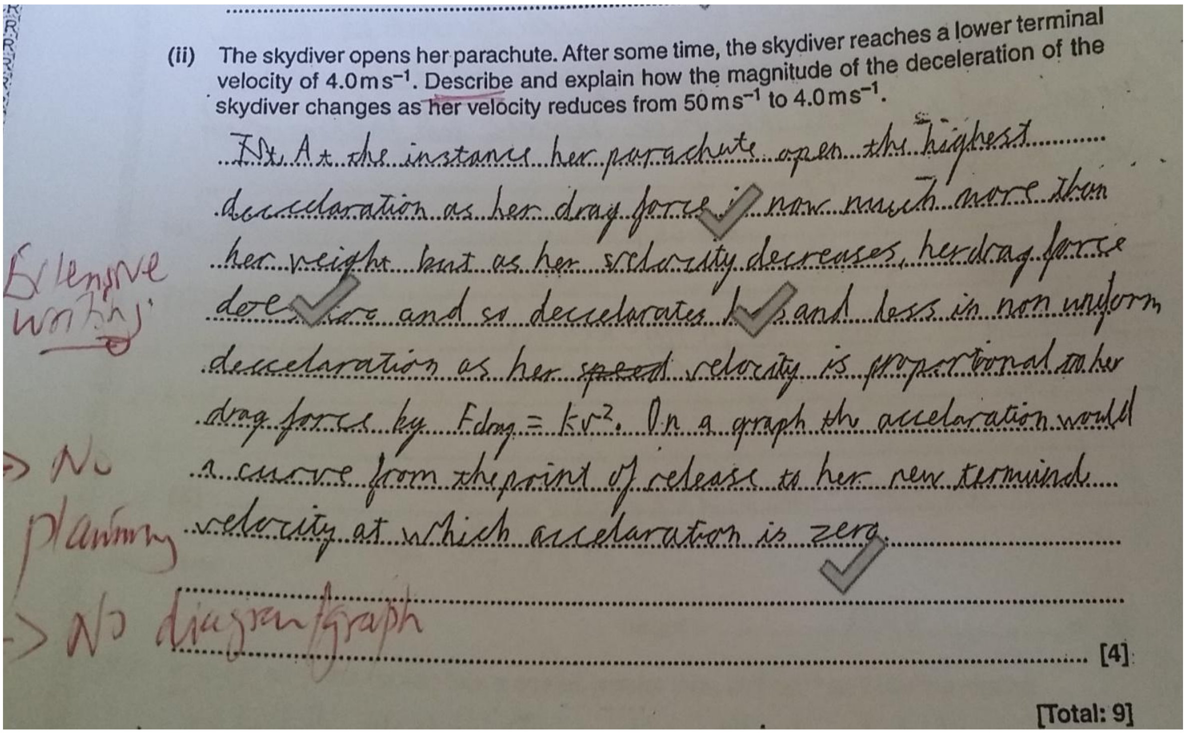
By taking moments about P, calculate the mass *m* of the suitcase.

$$50\,N \times (46 \times 10^{2}\,m) = Weight \times (32 \times 10^{2}\,m)$$
$$23\,Nm = Weight \times 0.32$$
$$\frac{23}{0.32} = Weight = 71.875$$
$$\frac{71.875}{9.81} = 7.32\,kg$$

Figure 4.3: Importance of data extraction

A few problems were detected with executing accurate mathematical procedures but this obstacle can be attributed to lack of problem comprehension and lack of schemata for the particular domain. Students failed to retrieve appropriate mathematical relationships for the given context.

In addition to some of the obstacles discussed above, qualitative analytical problems proved to be the biggest challenge. There is very little evidence of planning or modelling of the scenario with diagrams or equations as part of the planning. Rather than drafting a clearly, logically sequenced solution with an exploration of the causal links, some students rely on extensive writing. Figures 4.4 and 4.5 illustrate an extensive writing approach by two students, one predicted a B grade (Jamal) and the other, a D grade (Nik). With the extensive writing approach Jamal manages to score full marks. However, this approach results in a low score for Nik, a less able student.



(ii) The skydiver opens her parachute. After some time, the skydiver reaches a lower terminal velocity of 4.0 m s^{-1}. Describe and explain how the magnitude of the deceleration of the skydiver changes as her velocity reduces from 50 m s^{-1} to 4.0 m s^{-1}.

~~It~~ At the instance her parachute open the highest deceleration as her drag force is now much more than her weight but as her ~~s~~ velocity decreases, her drag force does [illegible] and so decelerates [illegible] and less in non uniform deceleration as her ~~speed~~ velocity is proportional to her drag force by $F_{drag} = kv^2$. On a graph the accelaration would a curve from the point of release to her new terminal velocity at which accelaration is zero

[4]

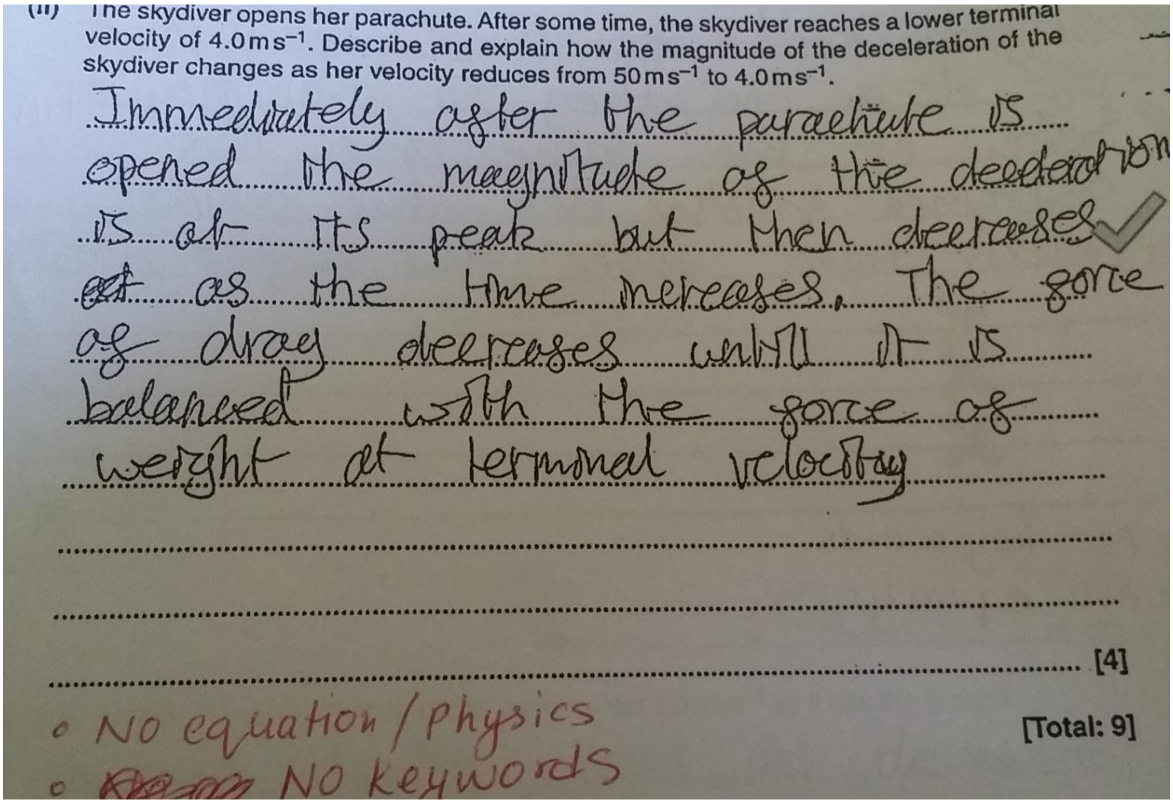
[Total: 9]

Extensive writing

-> No planning

-> No diagram/graph

Figure 4.4: Extensive writing for QL-AN problem by Jamal



(ii) The skydiver opens her parachute. After some time, the skydiver reaches a lower terminal velocity of 4.0 m s^{-1}. Describe and explain how the magnitude of the deceleration of the skydiver changes as her velocity reduces from 50 m s^{-1} to 4.0 m s^{-1}.

Immediately after the parachute is opened the magnitude of the deceleration is at its peak but then decreases ~~at~~ as the time increases. The force of drag decreases until it is balanced with the force of weight at terminal velocity

[4]

[Total: 9]

- NO equation / Physics
- ~~[illegible]~~ NO keywords

Figure 4.5: Extensive writing for QL-AN for Nik

4.2.3 Exam script analysis: A QCA approach

The main assumption with this QCA approach to data analysis was that written solutions and their steps were an overt manifestation of the cognitive processes involved in physics problem solving for the problems considered and their context. Metacognitive and collaborative competences could not be fully assessed using this data source.

A general framework for the analysis of the problem-solving process could be built from Pólya's 4-step problem-solving strategy (Pólya, 1957). In Pólya's model, the first step is *understanding the problem*. The solver identifies the unknown, the data and the problem conditions, and then draws a figure and introduces suitable notation. The second step, *devising a plan*, involves a search to connect the data and the unknown. If an immediate connection is not found, the solver considers related problems or problems that have already been solved, and uses this information to devise a plan to reach the unknown. In the third step, *carrying out the plan*, the steps outlined in part two are undertaken, and each step is checked for correctness. In the final step, *looking back*, the problem solution is examined, and arguments are checked. This approach highlights the importance of building robust problem-solving schemata and metacognitive processes of monitoring and evaluation.

The reviewed literature revealed two physics-specific strategies: Reif's 3-step model (1995) and that of Heller and Heller (2000). Reif's 3-step approach has the steps: analyse the problem; construction of a physics problem solving solution; and checks. The first step consists of generating a basic description of the situation and goals, including developing a refined physics description according to time sequences and intervals. The second stage involves identifying basic useful relations and implementing these relations. The final step requires the solvers to ask themselves if the goal has been attained, if the answer is in terms of known quantities and if there is consistency within the solution in terms of units, signs and scientific sense of the values.

The steps of the University of Minnesota problem-solving strategy (Heller & Heller, 2000) are: focus the problem; describe the physics; plan a solution; execute the plan; and evaluate the answer. In the first step, *focus the problem*, the solver determines the question, sketches a picture and selects a qualitative approach (Heller & Heller, 2000; Redish, 2003). The next step, *describe the physics*, includes drawing a diagram, defining the chosen symbols and stating quantitative relationships. The third step, *plan a solution*, entails choosing appropriate relationships between the quantities that define the problem, including the target quantity, undergoing a cycle of choosing additional relationships to eliminate unknowns and substituting to solve for the target. The fourth step, *execute the plan*, involves simplifying an expression and putting in numerical values for quantities if requested. The final step, *evaluate the answer*, requires the solver to evaluate the solution for reasonableness and completeness and to check that it is properly stated.

These three approaches seem to suggest a linear transformation of the problem statement, from words to visual representation in the form of a sketch, and then *to* a physical representation of the problem that includes a diagram and symbolic notation. The *planning a solution* further translates the problem into mathematical form using equations and constraints, which are further translated into mathematical actions to obtain an arithmetic solution in *execute the plan* (Docktor, 2000). The reality is, however, different; problem solving is not a linear process.

An adapted version of The Minnesota rubric was used for analysing the data (Heller & Heller, 2000; Docktor, 2009). The adaptations were compelled by the differences in the nature of problems used in the study by Docktor and Heller (2009) and those commonly found in GCE A-level physics. Docktor and Heller (2009) used mainly context-rich problems that were suited for the designed rubric. Parallels can be drawn between context-rich problems and qualitative analytical problems due to the demand for deep processing in both cases. A second consideration was to align the Minnesota rubric to the one used for analysing the exam scripts through retaining the main categories but adapting the subcategories after the initial trial coding.

The coding frame consisted of the main problem-solving process categories and at least two subcategories. The main categories reflect the aspects of the material being researched. The Minnesota rubric proposes five categories for cognitive competence assessment: focus the problem; describe the physics; plan a solution; execute the plan; and evaluate the answer.

In this study, for example, metacognitive processes had the following as the main categories: orientating; planning; execution; monitoring; and evaluation. As subcategories, the possible actions that reflected these underlying processes were added.

The coding frame met the following requirements: unidimensionality; mutual exclusiveness; exhaustiveness; and saturation (Schreier, 2012). The main categories covered one aspect of the material only: *unidimensionality*. The units were coded once under one category, meeting the second requirement of *mutual exclusiveness.* During the coding process, all the relevant material reflected one of the sub-categories and was assigned to a category and the residual categories were coded sparingly, meeting the requirement for exhaustiveness. To ensure *saturation,* all the subcategories were used at least once and no subcategory remained empty (Schreier, 2014). According to Strauss and Corbin (1998), saturation can only be met for data-driven codes. This occurs when looking at more material does not produce additional insights that give rise to new categories. However, for a concept-driven frame, some categories might remain empty (Groeben & Rustmeyer, 1994). These categories must still be part of the coding frame to start with.

After the initial coding frame was developed, with all categories generated and defined, the coding frame was revised. The focus was on identifying any overlaps in the subcategories and collapsing similar categories into one. There was no residual material to require formulation of new categories. Parts of the script were coded on three different occasions, separated by intervals of more than two weeks due to the absence of another coder. For trial coding, the developed coding frame was trialled on two occasions with a sample of the data (Kellehar, 1993; Ezzy, 2002). The results from this process were compared for consistency and variability. The categories, *focus the problem* and *describe the physics*; and *plan*, *execute* and *evaluate* proved to be closely connected and were merged.

After the trial coding phase, a few points were discussed during supervisory meetings but still considered by myself as a single coder, hence the decision to apply the coding frame to the same material at two points in time. Reliability of the coding frame means that two or more coders using the same units of analysis with the same frame, independently, will reach the same conclusion. For one coder, reliability translates to stable results when the same coding frame is used to analyse the same units over time (Creswell, 2009; Schreier, 2012).

As codes are redefined, the data previously coded must be re-examined. Transcripts were revisited to check the relevance of altered code definitions to non-coded data. A completely written problem-solving step was considered as the unit of analysis.

While Heller and Docktor's framework (2009) consists of five problem-solving processes, the final QCA framework for this study consisted of the three major executable categories for a successful solution that could be inferred from a written answer script. The initial coding of the data sample revealed the impracticality of coding for the fourth category, evaluation, from a written script. This category was removed from the coding frame. The first two categories, Focus the problem and Describe the physics, were collapsed into one category: Focus the problem. These categories are evident in video data. The subcategories for each were built from theory, data and practical experience as a physics teacher, to reflect the nature of the problems used in the GCE-A level physics.

With the categories developed, the data analysis involved reviewing each unit and categorising it according to the predefined categories. The main coding stage was executed using the final coding frame after trial coding. Table 4.4 shows the adapted coding frame for the external examination scripts.

Focus The Problem	1.	*Underline key aspects of problem; identify phenomena, variables and context, writing down the problem requirements explicitly.
	2.	*Extraction of relevant data in SF and SI units from question or graph.
	3.	Model of the scenario/situation
	4.	Annotating domain and fundamental; concepts + Laws
	5.	Approximations and assumptions
	6.	*Identify physical phenomena from graphs and annotate question
Plan The solution	1.	Diagram with physical quantities and symbols
	2.	Unknown and known quantities identified
	3.	All necessary fundamental equations and laws stated
	4.	Quantities to be calculated shown
	5.	*Draft showing logically sequenced key facts, variables and vocabulary.

	6.	Equations, key terms, diagrams or graphs included in draft.
	7.	*Extract information from graphical features : sections of graph showing same phenomenon variables, gradient, area under graph, units, intercepts
Execute the plan	1.	Substitution of variables proceeding to calculation of the desired quantities
	2.	*Use of units and standard form
	3.	*Degree of accuracy is specified
	4.	An answer to the original question is given
	5.	A clear, concise logically sequenced answer is given
	6.	*Cause and effect are clearly linked with causal mechanisms and the context explored.
	7.	*Physical analysis of scenario using graphs, equations, laws and models are used to support answer.
	8.	Basic recall of scientific knowledge.

Table 4.4: Exam script coding framework for OCR GCE-Physics (Adapted from Heller & Heller, 1992)

The final coding frame remained stable throughout the entire data coding process. Data from the G482 exam scripts was analysed using the same coding framework. Table 4.5 shows an extract of the analysis matrix built from this coding framework. On the coding matrix, success is indicated by a shaded box. In most cases, success means obtaining full marks or above half of the allocated marks for that part of the problem. The shaded boxes under each category represent the important subcategories that will lead to a successful solution of the problem.

		Question type	**Part question**	**Max Mark**	**Candidate**				**Executable categories**																				
					Sue	**Mik**	**Nik**	**Jamal**	**Focus the problem**							**Plan the solution**						**Execute the plan**							
1.	a)								1	2	3	4	5	6	7	1	2	3	4	5	6	1	2	3	4	5	6	7	8
2.	b)	Q N-	N	1	■ 1	■	■	■		■								■				■	■						
	c)	Q N-	N	3	■ 3	■	■	■																					
	d)	Q L-	Y	3	0			■			■		■						■		■					■	■		

	e)	QL-	N	4	1			■			■	■							■							■	■		
3	a	QL-	N	1	1	■		■			■								■										■
	B	QL-	N	1	0			■		■				■					■			■	■						
	C i	QL-		3	3	■	■	■		■				■					■							■			
	ii	QN-		3	3			■						■	■			■				■							■
	iii	QL-	y	2	0				■	■	■					■	■					■	■						
4	a	QL-		1	1	■	■	■																					
	B	QL-	Y	3	1			■	■				■	■		■			■		■					■	■		
	C i	QL-AN	N	1	1	■	■	■	■		■					■										■	■		
	C ii	QL-AN	Y	4	4			■	■										■		■						■	■	
5	a	QL-	N	1	1	■		■	■			■					■											■	
	b i	QN-	N	2	2	■		■		■		■				■	■	■			■	■	■		■				
	b ii	QN-	Y	3	0					■											■	■			■				
6	a	QN-	N	3	0	■		■	■		■		■				■				■	■					■		
	B	QL-		1	0				■				■				■									■	■		■

Table 4.5: A matrix of the QCA coding framework for the G481 script

The intensity of the executable episode, i.e. the frequency with which the code occurred, gave an insight into the cognitive demand placed on the solver for the different problem categories. This intensity was for the G481 examination paper but highlights the depth of the cognitive demand when solving QL-AN and QN-CAL problems. A summary of the executable processes as evidenced by the problems in G481 is given in table 4.7. Table 4.6 gives a summary of the key episodes for each problem category as evidenced by the data analysis.

Problem type	**Focus**	**Planning**	**Execute**	**Total**
QL-B	**12**	**9**	**5**	**26**
QN-CAL	**14**	**14**	**17**	**45**
QL-AN	**24**	**13**	**19**	**56**

Graph	**6**	**5**	**1**	**12**

Table 4.6: Frequency of executable processes

Type of problem	**Executable episode of the strategy**		
	Focus the problem	**Plan the solution**	**Execute the plan**
QL-BR	**1.** Underline key aspects of the problem and identify phenomenon, the variables and context. **2.** Explicitly write the problem requirements. **3.** Model the scenario/situation. **4.** Write down approximations or assumptions.	**1.** State and write all fundamental equations and laws. **2.** Make a draft showing logically sequenced facts, variables and key terms.	**1.** A scientific analysis of scenario using graphs, equations, laws and models are used to support the answer. **2.** Write down a clear, concise and logically sequenced answer. **3.** Cause and effect are linked with all causal mechanisms and the contexts are well linked and explained.
QL-CAL		**1.** Diagram with physical quantities and symbols. **2.** All necessary quantities and equations identified with quantities to be calculated shown.	**1.** Substitution of quantities and calculations of the desired quantities. **2.** Use of appropriate units and standard form. **3.** An answer to the original question is provided.
QL-AN		**1.** Diagram with physical quantities and symbols. **2.** All necessary quantities and equations identified with quantities to be calculated	**1.** Physical analysis of scenario using equations, laws, graphs, laws and models are used to support the answer. **2.** Write down a

		shown. **3.** Draft showing logically sequenced key facts, diagrams, graphs, variables and vocabulary.	clear, concise and logically sequenced answer. **3.** Cause and effect are linked with all causal mechanisms and the contexts are well linked and explained.
Graph	Identify physical phenomena from a graph or to construct a graph.	**1.** Extract and write down information to analyse a given graph or to construct the graph.	

Table 4.7: Summary of executable episodes from an analysis of G481

Summarily, responding to the research question from a thematic analysis perspective, the G481 scripts revealed a novice approach to problem solving by all four students. For low demand problems, basic qualitative, students can recall basic concepts. However, there is low attainment for slightly more demanding problems that require the retrieval of more than simple concepts. All the four students demonstrated lack of an appropriate effective strategy in solving QL-AN. These are high demand problems that require a solver to ‘explain’ and ‘describe’. There is no evidence of planning and logical progression in the formulation of the solution. Causal links are not explored using appropriate physics laws in the form of equations or using models.

While thematic analysis revealed how students performed in the different problem categories of the G481 exam and how they approached the problems, QCA revealed the same pattern but gave an insight into how the problems could have been successfully tackled. The real, existing scenario is painted from thematic analysis and the desired one is portrayed by the categories designed in QCA. Thematic analysis gives the starting point for intervention as it portrays the current situation in problem solving as per the research question and QCA confirmed the identified areas of focus and the desired goals after intervention.

4.3 Video data analysis

This section discusses how entry data from videos were analysed to respond to the first research question: *How do A-level physics students in an inner London comprehensive school approach physics problem solving?*

The first section focuses on analysing the video data for cognitive-metacognitive processes. The theoretical underpinnings of the QCA frameworks used for video data analysis are discussed. The framework for cognitive-metacognitive competences is built from the work by Meijer et al. (2006) on physics problem solving and Armour-Thomas et al. (1995), and Schoenfeld (1985) in mathematical problem solving (table 4.8).

Section 4.4 discusses the framework for the analysis of collaborative competences during CGPS. The framework built from the theoretical perspectives on collaboration by Roschelle and Teasley (1995) and the PISA 2015 draft for assessing collaborative problem-solving (OECD, 2014). To illustrate the application of the framework for assessing collaborative competences (Table 4.1) a segment of the data from exit CGPS video is coded (table 4.11). Section 4.4.4 briefly discusses the assessment of self-efficacy and a detailed discussion of the results from the video data analysis for each student is undertaken. For each data collection stage for the different data collected, self-efficacy, cognitive, metacognitive, cognitive and collaborative competences are probed and any shifts noted for each student.

4.3.1 Analysing the video data for cognitive-metacognitive processes

From the information processing theory and the verbalisation theory (Simon & Newell, 1972, 1993) problem solving proceeds through a sequence of steps, each of which changes the knowledge that a person has about the problem at hand. As the process progresses, the information that resides temporarily in the working memory is heeded during verbalisation.

Verbal protocols are considered controversial due to the highly subjective nature of their data. The question that requires an in-depth examination is whether transcripts from the think aloud protocols provide accurate reflections of the process (Schoenfeld, 1985). Major proponents for this approach, e.g. Ericsson and Simon (1993), argue that verbal reports are veridical (they provide information reflective of the actual cognitive processes) to the extent that they involve output from the working memory and that subjects can provide self-reports through think-aloud interviews that are non-reactive, i.e. the act of thinking aloud does itself not contaminate the subject's verbal process. Even if this tends to slow the cognitive process relative to silent control condition, they argue, it does not fundamentally alter the subject's level of task performance and the effects on task performance are relatively minimal compared to other features of the experimental set up. However, a limiting factor on the use of protocols is that complex or non-verbal information in the working memory cannot be verbalised.

The coding and analysis of the empirical (verbal and non-verbal) data generated from these protocols has to take place in some kind of theoretical context (Ericsson & Simon, 1993). The pertinence of the data to the ongoing cognitive processes is judged against the criteria proposed by Ericson and Simon (1993). To be used to infer to underlying cognitive processes the verbalisations should be relevant to the task and logically consistent and a subset of the information heeded during task performance should be remembered (p.171). To maintain objectivity in the data generation process, coded protocols are treated as data in the sense that the coding involves procedures and the coding scheme used is based on a psychological model and a verbalisation theory (Van Someren, 1994).

The analysis using the established QCA frameworks sought to capture in as much detail as possible the objective traces of the sequence of overt actions that depict the underlying cognitive, metacognitive, self-efficacy and collaborative process as the student attempted to solved the problems.

Before the main analysis through QCA, the video data in the form of actions and verbalisations during the problem-solving sessions were transcribed using indexical and unfocussed transcription (Gibson & Brown, 2009). With indexical transcription, the data were set in relation to a timeline to help locate where certain processes or actions occurred or should have occurred but didn't. The precision of the timeline, 30 seconds, was the shortest time perceived for a cognitive or metacognitive process and its verbalisation to occur. The 30 seconds precision was considered from the analysis of the scripts which showed this as the average duration that would correspond to the unit of analysis. With the unfocussed transcription, the aim was to create a record of what happened within a given recording of speech or action. No effort was made to represent the interactional characteristics unless they were related to problem solving. Pauses of more than three seconds were noted. Whether others would parse and code the protocol into the same episodes or see the same critical moments haunts the choice of this method; it raises the question of reliability and replicability. During problem solving, behavior is meant to be overt but sometimes the most important event is one that does not take place.

The framework for cognitive-metacognitive competences was based on the categories proposed by Meijer et al. (2006) on physics problem solving and Armour-Thomas et al. (1995), and Schoenfeld (1985) in mathematical problem solving was then used to analyse the episodes for metacognitive processes. The raw data in the form of segmented protocols were parsed into episodes. An episode is considered as a period of time in which the problem solver, the participant in this study, is engaged in a single set of actions of the same type (Schoenfeld, 1985). The episodes were categorised as orientating, planning, execution, monitoring and evaluation.

There exists a blurred line between these episodes that reflects the underlying metacognitive processes and the cognitive steps (*focus the problem, describe the physics, plan a solution, execute the plan* and *evaluate the answer*) outlined by Heller and Heller in the Minnesota framework. Although Artzt and Armour-Thomas (1992) attempt to differentiate conceptually between cognitive and metacognitive processes, operationally the distinction is blurred (Artzt & Armour-Thomas, 1992). The episodes for this study were coded as cognitive-metacognitive. Coding metacognitive processes must also identify the loci of strategic decisions, both those that should have taken place during problem solving but didn’t and those that did take place (Schoenfeld, 1985). From the protocols in this study, these are episodes where major shifts in resource allocation happen. As an example, during CGPS, new information or contribution leads to the taking of a different approach and the episode is terminated with a clear new direction in the problem-solving process. Another instance where executive decisions of control must occur is when execution bogs down and the process degenerates into less structured trial-and-error explorations.

In addition to coding cognitive and metacognitive processes, physics problem-solving competences were coded using an adapted problem-solving competence rubric (Docktor, 2009). These competences are *useful description, physics approach, specific application of physics, mathematical procedures* and *logical progression (*Docktor, 2009). *Useful description* refers to the process of translating the problem statement into an appropriate and valuable form such as assigning mathematically useful symbols to quantities and/or visualisation through modelling using a sketch, diagram or graph. *Physics approach* involves selecting appropriate physics concepts and principles for the problem and demonstrating a basic understanding of those concepts. *Specific application of physics* is the process of linking concepts and principles to the specific quantities and assumptions in the problem. *Mathematical procedures* include the mathematical operations used to obtain the desired physics quantity. *Logical progression* is an overall category that assesses the extent to which the solution is focused and consistent. During coding, logical progression can only be inferred from the whole process rather than as a single episode.

The triggering of mechanisms of metacognitive processing is evidenced by decisions or verbalisations that reflect orientating, planning, execution, monitoring and evaluation. From the video data, this triggering can be identified as points where there is a shift in resource allocation or change in the nature of episode, a change in approach or the search for a new solution in light of an evaluation of the progress. The analysis also highlighted areas where students should have timely noted their lack of progress, errors in procedures, and decision to persist or move on.

In addition to a monitoring process which merely serves to confirm that all is well, common with novices, more controlled monitoring and regulatory processes are triggered when students become aware of specific difficulties. These instances are sought in the data as evidence of expertise. Schoenfeld (1985) argues that purposeful monitoring triggers metacognitive ‘red flags’, signalling the need for a pause or some backtracking while remedial action is taken. Data analysis also has to identify instances where monitoring would have stopped students from embarking on a ‘wild goose chase’. In problems that involve calculation, for example, error detection during an execution episode should prompt checking and correction of calculations carried out so far. If attempts to verify the solution reveal that the answer does not satisfy the problem conditions, or does not make sense, then this anomalous result should trigger a calculation check (assess execution of strategy), followed, if necessary, by a reassessment of the strategy. The main metacognitive processes categories are illustrated in table 4.8 with some of the actions that form the subcategories.

Metacognitive process	**Possible actions**
A. Orientating	• Reading the problem. • Identifying or repeating important information, establishing given data, observing diagrams, tables. • Identifying type of problem (problem schema): have I/we solved a similar problem? • Assessing self-efficacy through rating scales for each task.
B. Planning	• Keep on reading, hoping for clarity. • Choosing a strategy to see if it works: trial and error, drawing a graph to aid solution. • Adopting a model, assumption, using a known simpler model to approximate. • Drawing a diagram as part of a step.
C. Executing	• Coherent, well structured, systematic and deliberate execution of action plan. • Converting units, estimating calculations, substituting given values. • Drawing a diagram: verbal to visual (diagram, graph, table, tally), writing the final answer.
D: Monitoring	• Checking the state of the work and progress • Considering reallocation of resources e.g. time • Comprehension failure • Noticing problem difficulty, changing decision: strategy, task
E: Evaluation	• Checking if outcome reflects problem understanding. • Confident about a procedure or solution of a task or subtask • Commenting on problem difficulty

Table 4.8: Metacognitive analytical framework

The following section illustrates how this framework was used to analyse data from the individual problem-solving sessions.

4.3.2. Analysis of the individual problem-solving videos

i. Explaining the coding matrix

An illustration of how all the individual video data were transcribed, coded and analysed using the discussed frameworks is provided using the example below. Critical moments are identified when an important decision is taken (black triangle) and when an important decision should have been taken but was not taken (inverted triangle), e.g. monitoring of the process or progress should have been done. The cognitive-metacognitive processes are coded as follows:

A: Orientating
B: Planning
C: Executing
D: Monitoring
E: Evaluating.

Cognitive competences are given the following codes on the matrix:

i. Useful description
ii. Physics approach
iii. Specific application of physics
iv. Mathematical procedures
v. Logical progression.

The time frame is divided into 30 seconds intervals, as discussed above. Individual actions are those overt actions geared to problem solving, e.g. reading the problem statement, and writing down a solution step. *Verbalisations* include what the solver says audibly and a **commentary** reflects the coder's view to the verbalisation or action with regard to problem solving. This approach to coding video data from CGPS using this framework is exemplified in table 4.9. It must be noted that *logical progression* as a competence reflects a summative approach rather than an episodic competence like *mathematical procedures*. An analysis of the whole problem-solving process is required to judge logical competence. Examples of protocols for the other students are provided in appendices six to nine.

Name: Jamal **Date**: July 12, 2013 **Topic**: Electricity

Time frame	Individual action + *verbalisations* + **commentary**	Self efficacy (SE)	Cognitive-metacognitive					Competences				
			A	B	C	D	E	i	ii	iii	iv	v
00:00	Reads question slowly ...		■									
00:30	*"... complete the circuit ... ok...all right I am just going to draw the ...."* underlines the key words then proceeds to draw the circuit.			■	■			■				
01:00					■							
01:30	Draws the circuit and scores three marks in one minute. Proceeds to part (ii)	■			■					■		
02:00 ▲	Good progress…scores two marks in one minute		■									
	Pauses and looks at question. **Monitoring comprehension**					■						
	Re-reads the question.		■									
	"... *all right* ..." picks ruler and re-reads the question again.		■									
02:30	Re-reads question again, underlining key points. **A qualitative analytical problem.**	■	■									
03:00	" ... *Internal resistance* **...** *so* ... *.if you change* ..." **Does a mental analysis.**	■		■					■			
03:30	"*...therefore...*"	■	■						■			
	"... so V = I(R+r) .emf is constant ...if the resistance of the resistor goes down, therefore current will go up… therefore it means the terminal p.d will decrease ... "			■							■	
▲	**The student persists with the somewhat incomprehensible problem**			■								

	retrieves the equation and proceeds to explore causal links.			■								
04:00 ▼	**A rough plan on the side would have helped to crystallise the ideas**			■								
	"... so what will be the reason why ...it says suggest why ...?" underlines the key part of the question.					■						
04:30 ▼	Proceeds to write down final answer "... *lowering the resistance ..."*				■							
	Stops to read the answer.					■						
07:00 ▼	**Lack of initial planning leads to loss in pace.**				■							
07:30	Moves to next question. Reads question slowly "... *ahhh* ...."			■								
08:30	*"... OK so the power dissipated is ...P= I squared R ...we need to work out the value for R which is V/I ..."*									■		
▲	**Good question comprehension. Accurate retrieval of equations**									■		
09:00	Reads on "... *justify that the maximum is at or near point B ..."* underlines the word <u>justify.</u>		■									
	"... I am not sure what I am about to do ... "						■					
	Keeps reading for comprehension and cues.			■								
10:00	Writes down P = I^2R.					■					■	
▲	*"... Ok ... I have to take values for those points. At point A, I equals to 0.35 A, R equals to ..."*...searches the graph for more data and picks a calculator, calculates R. **Good break through and perseverance indicating high self-efficacy**	■					■					

	Continues to read the graph and calculates power at points A and C						■					
11:30	*" ... power at C is 0.325 W ... "*				■	■	■				■	
12:00	Goes through the calculations.					■	■					
▲	Double checks the calculations again on the calculator**. Good monitoring of quality of work before proceeding**.					■					■	
▼	**Writing down key steps and extracting data from graph would have made it easier to plan.**					■						
12:30	Double checking the calculations					■	■				■	
	"... I am not sure what ...." Re-reads question and picks calculator.	■				■				■		
13:00	"... power at B will be ...7...8 **..."** reads graph from graph for voltage values, calculates power at B and leaves answer on calculator. **Reduced number of steps leaves solution unclear, a few missed steps**.			■						■		
14:00 ▼					■							
14:30	*"... as the power of B is higher ...mmmm ... "* Writes and cancels the answer...re-writes.				■	■				■		

Table 4.9: An extract to provide an example of an individual protocol for a problem on electricity by Jamal

4.4 Framework for analysis of collaborative competences during CGPS

4.4.1 Theoretical background

To analyse collaborative competences during CGPS sessions, a framework was built using theoretical perspectives on collaboration by Roschelle and Teasley (1995) and the PISA 2015 draft for assessing collaborative problem-solving (OECD, 2014).

Roschelle and Teasley (1995) define collaborative problem solving (CPS) as a coordinated, synchronous activity that is the result of a continued attempt to construct and maintain a shared conception of a problem through a coordinated production of talk and action. The process tends to be inherently interactive, interdependent and dynamic (Klieme, 2004; Wirth & Klieme, 2004; Blech & Funke, 2010). During the CPS process, students externalise their knowledge, articulate and negotiate alternative perspectives, inducing reflection on the meaning of the arguments put forward by peers (Andriessen, 2006).

Collaborative problem solving competency is defined as the capacity of an individual to engage effectively in a process whereby two or more agents attempt to solve a problem by sharing the understanding and effort required to come to a solution and pooling their knowledge, skills and effort to reach that solution (PISA, 2014). This negotiated construction of knowledge through dialogue and collaborative argumentation takes place within a joint problem space (JPS) constructed and maintained by the agents (Roschelle & Teasley 1993).

A JPS is defined as an emergent, socially-negotiated set of knowledge elements, such as goals, problem state descriptions and problem-solving actions, constructed through an external meditational framework of shared language and activity (Teasley & Roschelle, 1995). As a shared knowledge structure that supports problem solving, a JPS integrates shared understanding of the problem state, goals, descriptions of the current problem state, awareness of available problem actions, and associations that relate goals to the features of the current problem state, and available actions (PISA 2014; Fiore et al., 2010; Dillenbourg, 1999; Teasley & Roschelle, 1995).

Within the JPS, the process of the students' incremental achievement of convergent meaning through interaction can be characterised by interactive cycles of conversational turn-taking and the application of progressively higher standards of evidence for convergence (Roschelle, 1992). A common understanding, rather than a common intersection of overlapping sets, leading to a shared "shared agreement" or a "mutual conception of the problem" tied to the context of activity, is reached (Salas & Fiore, 2004).

Collaboration is achieved when students are presented with conflicts, are engaged in argumentative processes and manage to arrive at a shared problem solution. Argumentation is considered an important mechanism for fruitful discussion and production of constructive activities (Andriessen, 2006). Argumentation provides an opportunity for appropriation through negotiation. Argumentation is defined as the process of a structured connection of claims, evidence and rebuttals, producing the argument (Kanselaar et al., 2002). During problem solving, group members are provided with an opportunity to challenge other group members' current views. Such interactions are a source of cognitive conflicts that stimulate cognitive development at an individual level and at a social level through the interactive construction of knowledge.

An argument provides an opportunity for appropriation through negotiation (Piaget, 1977; Von Glaserfeld, 1989; Greeno, 1997). In argumentation, students can give prominence to conflict and negotiation processes, critically discuss information, elaborate on arguments and explore multiple perspectives. Members must justify or defend a proposal, and/or argue and reformulate a strategy. Knowledge and opinions can be constructed or reconstructed, expanding students' understanding of concepts and problems. Incomplete, doubted, conflicting or disbelieved information is critically checked, challenged or countered on its strength (is it true, is it relevant?) until finally a shared solution is agreed upon (Veerman, Andriessen & Kanselaar, 1999). Succinctly, effective collaboration argumentation is evidenced when students share a focus on the same issues and negotiate about the meaning of each other's information.

4.4.2 The CGPS data analysis framework

Assessing collaborative competences required the capturing of the communication stream through videos during CGPS. The analysis of the content and structure of communication streams provided measures of collaborative competencies.

The video data, actions and verbalisations were transcribed and analysed to determine the underlying processes. An examination of students' discourse and activity as they work together allows us to understand how the social interaction affects the course and outcome of problem solving. To unravel a shift in regularities, competencies are inferred from the actions performed by the individuals, communications made to others, intermediate and final products of the problem-solving tasks, and open-ended reflections on problem-solving representations and activities. Unravelling this shift in regularities requires an understanding of how students use coordinated language and action to establish shared knowledge, to recognise any divergences from shared knowledge as they arise, and to rectify misunderstandings that impede joint work.

Three frameworks for assessing collaborative competencies were reviewed and used to build a framework for analysing collaboration in CGPS videos (Roschelle &Teasley, 1995; Veerman, Andriessen & Kanselaar, 2006; PISA, 2013). Roschelle and Teasley (1993) argue that a successful collaborative interaction between participants is one where there is evidence of positive interdependence, promotive interaction, individual accountability and group processing. During such an interaction, meaning is coordinated and mutual intelligibility achieved as students provide constant evidence, positive and negative, that each utterance has been understood, and engage in repairs when it has not. The main categories adopted for the framework were *positive interdependence, promotive interaction, individual accountability* and *group processing* (see table 4.10). The subcategories were derived from all the three frameworks. However, at times the absence of a clear distinction between these main categories makes the coding process a product of the subjective decisions of the coder.

A. Positive interdependence	*a.* **Constructive feedback**. Members give constructive feedback to facilitate a reflection and evaluation on the success of the group organisation in solving the problem. *b.* **Coordination of language and action**. Team members' discussion shows collaborative turn sequences, specific turn-taking and narrations. *c.* **Establishing and maintaining team organisation.** Students assume different roles for the effective functioning of the group, monitor the group organisation and progress, and facilitate changes needed to handle communication breakdowns, obstacles to the problem, and performance optimisation.

B. **Promotive interaction**	*a.* **Constructive discussions.** Students’ input related to the problem to be solved results in content being added, explained, evaluated, summarised or transformed. *b.* **Monitoring and maintaining the shared understanding**. Students establish or negotiate shared meanings, verifying what each other know, and taking actions to re**pair deficits in shared knowledge.** *c.* **Collaborative argumentation.** Students put forward suggestions for the analysis and solution of the problem, challenge their proposals, back them up with theory, rebut opposing views on theoretical grounds, and weigh the available evidence that favours or disfavours possible solutions. The meaning of each other's information is negotiated. Students critically and constructively analyse others´ contributions through argumentation sequences.
C. Individual accountabi	*a.* **Assumption of different roles**. Students respond to requests or take actions that are relevant to any progress toward goals. *b.* **Consistent engagement**: Reduced or no instances of social loafing (which lead to low productivity in the group through not contributing).

***D.* Group processing**	*a.* **Establishing and maintaining shared understanding**. In establishing the joint problem space students identify the mutual knowledge (what each other knows about the problem) and the perspectives of other agents in the collaboration, and establish a shared vision of the problem states and activities. Group efficacy is established by comparing confidence levels. *b.* **A shared focus.** Students use conceptual knowledge to explore and propose a strategy to solve a problem or to support a claim. Students plan how to start the task, time management, how to carry out the task etc. *c.* **Repairs.** The group collectively explores the weaknesses and merits of each proposal and individual ideas are negotiated with respect to the shared work. Students resolve dissension or conflict among group members and identify and rectify errors committed by group members. *d.* **Taking appropriate action to solve the problem.** The group identifies and describes the problem to be solved, creating a shared understanding of the problem state, goals and descriptions of the current problem state. The group agrees on the strategies to adopt and enact to solve the problem. The group monitors the results of actions and evaluates success in solving the problem.

Table 4.10: A framework for assessing collaborative competences

To illustrate the application of this framework, low collaborative competence was evidenced by communications irrelevant to the task, providing redundant, repetitive or incorrect information to other group members, random actions or communications that do not reflect any meaningful role, a trial-and-error approach that moves the problem away from the solution and /or taking actions that are independent or inappropriate for the assumed role or tasks. Solving a problem alone, when interdependency was required, was considered evidence of low competence, albeit a successful solution.

A student who participates in modification of plans and tasks without initiating the modifications can be regarded as having a medium collaborative competence. Medium collaborative competence is generally evidenced by not taking an initiative but positively responding to requests to clarify problem goals, problem constraints and task requirements.

The actions follow the planned tasks for particular roles in the agreed JPS with evident efforts to repairs deficits in shared understanding when prompted.

A student with high collaborative problem-solving competence identifies efficient pathways to goal resolution and takes an initiative to build and maintain the JPS by enquiring about the abilities and perspectives of other group members. In following the agreed plan, the student initiates requests to clarify problem goals, common goals, problem constraints and task requirements when contextually appropriate. When enacting agreed plans, a competent collaborator detects deficits (gaps or errors) in shared understanding and takes the initiative to perform actions and communication to solve these deficits. In the event of a problem with the chosen solution strategy, the highly competent collaborator takes the initiative to identify, propose, describe or change the plan. For effective group functioning, the highly competent collaborator plans the different group roles and monitors the actions of others on the team.

During collaborative problem solving, students can assume different roles, i.e.: f*acilitator, proposer, supporter, critic* and *recorder*. The *facilitator* (**F**) invites participation, monitors the group's progress and promotes group harmony by tempering conflicts, building group harmony, etc. The *proposer* (**P**) suggests new ideas that support a chosen approach, citing advantages and disadvantages of the proposed strategy. A *supporter* (**S**) tries to justify a claim, elaborates it and tends to reinforce the direction of the current problem-solving approach. A *critic* (**C)** challenges the original claim and identifies errors and weaknesses suggesting related alternatives that tend to alter the course of the problem-solving process. The critic usually triggers the argumentation process. A *recorder* (**R**) `distils´ and summarises the jointly constructed solution path. The following section illustrates how the video data was analysed using this framework. A recorder is also described as scribe in this study.

4.4.3 *Analysis of the CGPS videos*

Participants: Jamal, Sue, Mik and Nik

Date: 18/10/2013

	Action **+** *verbalisations* **+ commentary**	**Role**	**SE**	**Collaborative**				**Cognitive-metacognitive**					**Competences**				
				I	II	III	IV	A	B	C	D	E	1	2	3	4	5
0:00	*Group allocates initial roles*						■								■		
01:00	Jamal ... reads question 1 ...						J	J					■				
	Sue. " ... kinetic energy is not conserved … "	P(S)					S	S						■			
	Mik. "...yeah that means momentum is conserved … "	S(M)			M			M									
▲	Sue. "...the second ...is not...become in inelastic collisions KE is conserved …" **Quick retrieval – evidence of schema.**						S			S							
	Nik. "... does it mean the same as before or the same for each? … "						N										
▲	Jamal. " ... let´s do the confidence ratings for each question first … " **Shift from general approach to strategic planning**.		■	J				J						■			
02:30	Nik. " ... right question A … "																
	Sue . "... you don't have to do all of it, do part … "	C(S)													■		
	Nik. reads question " … kinetic model of ideal gases … "																
	Jamal. " ...i will say 50 % ... " Mik. " … i will say 60 % … "	P(M&J)	■				■						■				
	Jamal-explain how lift force maintains.. Sue: " … I think that's 70% … "						■								■		

03:00	Jamal. “ ...i think thats over 70% , 80 % ... ”		■				■										
	Mik. “ ... i will give that 70 % ... ” Sue. “... yeah that´s 70 % ... ”		■				■										
03:00	Nik “... let’s go to B ... ”						■										
	Sue. “ ... i think that’s all right...that’s just dividing the equations ... ”	P(S)					■									■	
	Jamal . “... i would say 80% ... ”		■				■										
	Mik “...i would say 80 % ... ”		■				■										
	Sue . “ ... that’s easy ... it´s easy ..(reads on) ...not actually ... ”								S								
▲	**Re-assessment of knowledge after re-establishing problem demands.**										■						
03:30	Nik . “ ... simple harmonic motion ... ”	P															
	S. “ ... not that one, we haven’t done C ... ”																
	Jamal . “ ... I would say 75, whole C I will say 65% ... ”		■														
	Mik. “ ... second part I would give that 70 % ...”		■														
04:00	Mik..(***reads***) “ ... will give that 10* .... ”																
	Jamal ...3a																
	N. “ ...yeah that’s pretty much ... ”	S(N)	■														
	S. “ ... it has to move from equilibrium position ... ”	S(S)		N					S					■			
▲	Nik . “... and directly towards it and proportional to the displacement ... ”	S(N)		S						N							
▼	**Rood definition but use of equation would have helped further exploration.**			■										■			

04:30	J. " ...that's the definition ?Fair enough ... "									■							
	S. "...part C..90 to 95 % confidence level ... " **Group scans question**	F(S)	■														
	Mik. "...Yeah, i think its fine ... "	S(M)															
05:00	Jamal." ... use of resonance? ... "				■												
	Nik. " ... i think it's when we have to ... "	P(N)			■			■ N									
	Jamal. " ... but that's not useful ... "	C(J)			■ J			J									
	Nik ...but I thought resonance ... there has to be the same frequency				■ N												
	Jamal . "...Yeah ... Which means the amplitude ... "*M explains*				■ M							■					
▲	**Argumentation between Nik and Jamal on resonance.**																
	Nik . "... I think we can say we have 50 % here ...we can get half the question ... "	F(N)							■								
06:00	Sue . " ... we start solving the problems...the first one has the highest rating ... "	F(S)	■				■ S										
▲	**Adoption of strategy, problems with highest confidence rating first.**						■										

Table 4.11: Coding data from a CGPS exit data video

4.4.4 Assessing self-efficacy

One's perceived capabilities for successfully solving a problem, derived from mastery experiences, vicarious experiences, forms of social persuasion and physiological indices, will determine whether one will engage and persist with the problem or not (Bandura, 1977). This study argues that self-efficacy beliefs influence how the individual will contribute during collaborative group problem solving, influencing group efficacy. The individual´s self-efficacy is in turn transformed by the collaborative process, a bi-directional relationship.

An initial attempt to assess self-efficacy using rating scales was discontinued as a data collection method due to validity problems: it was noted that some students who wouldn't engage with basic mechanics problems rated themselves above 80% on all items including reverse items. To reduce response bias, self-efficacy was inferred from verbalisations and assessment of self-confidence through a rating scale of 0 to 100 for each given problem before engaging with it. When successes are hard to come by, individuals of high efficacy are persisters and those of low efficacy are rapid quitters (Bandura, 1997; Bandura & Schunk, 1981).

4.5 Results from the video data analysis for each student

This section presents the results from the analysed video and audio data, individual and collaborative, for each of the four students.

4.5.1 Findings for Jamal

A. Entry Findings before the intervention

i. Metacognitive competencies

The student proceeds to attempt to solve the problems immediately after reading the question demands. There is no evidence of time dedicated to ensure problem comprehension. As evidence of lack of comprehension or planning, the student repeatedly reads the problem (07:16 to 10:12), eventually moving back to problem 1, where he substitutes the data into the formula. There is no orientation or planning in context-rich or quantitative-analytical problems, problems that require an in-depth analysis. There is some evidence of monitoring of the problem comprehension, e.g. 09:36 w*hat´s the question actually*? The student re-establishes the problem demands. Final solutions are not evaluated which can be interpreted as an indication of high confidence. Some marks are lost due to inadequate problem comprehension. The solutions offered do not fully attend to the problem demands, a result of poor monitoring! Upon encountering difficulties with one problem, this high ability problem solver does embark on a random trial and error search for a solution path but reallocates resources to another task.

ii. Cognitive competencies

The student does not perform a thorough initial qualitative analysis of the problem, resulting in lack of modelling of the physical phenomenon as part of the orientating or planning phase. There is no data extraction, resulting in an inadequate *useful description*. However, the student selects appropriate physics concepts related to the problem, demonstrating a good physics approach. A good *specific application of physics* is evidenced by a clear application of the physics concepts and principles to the specific conditions in the problem. This suggests evidence of an existing problem-solving schema for low demand routine problems, e.g. *Calculate the net force on the aircraft to produce this accelerating force.* Between 01:00 and 02:33 orientating, planning and execution are carried out simultaneously with no monitoring or pause.

Algebraic manipulations and substitutions are performed at a seemingly automated level, demonstrating excellent *mathematical procedures.* However, there is evidence of poor *logical progression.* There is no clear strategy to solving the problems and the student adopts mainly a trial-and-error approach for the high demand context-rich problems. There is overreliance on mathematical skills rather than physics knowledge or use of strategies. The solver weaves between two problems, questions 1 and 2. This increases his cognitive load! The constant re-reading points to the lack of cognitive load reducing strategies. The solution to question 2 is determined a series of logical reasoning steps, analysing the causal relations without recourse to physics calculations. Despite the issues discussed the solver scores 14 marks out of the possible 15.

iii. Collaborative competences

The CGPS video data suggest a low *positive interdependence* where the student works in a dyad. During the session there is very little collaborative-turn taking. Jamal starts the problem individually rather than initiating to facilitate an initial shared understanding of the task to establish the joint problem space. There is no clear evidence of efforts to have an initial group planning by discussing with Mik for the joint co-construction of the problem-solving strategy. *Promotive interaction* is low as Jamal fails to establish what Mik knows to allow for collaborative turn-taking. The interaction is reduced to prompting and asking for opinions when stuck. However, there is good *individual accountability* as Jamal assumes different roles and identifies efficient pathways towards a solution, detecting defects and inviting Mik to help explore the problem space. Evidently, there is low *group processing* as there is no clear collective exploration to build the joint problem space. There is no clear causal exploration of problem, relying on a trial-and-error approach. The communication does not allow for a collective approach to build a shared understanding.

iv. Self-efficacy

When asked to rate his confidence on each of the three problems, Jamal has confidence ratings of 95% for all the three problems. The results and time dedicated to the solutions verify these confidence ratings. Despite the novelty and complexity of the two context-rich problems, the student calmly and successfully solves all the problems through mathematical modelling and trial and error. The student is calm and persistent, relying more on mathematical prowess, persevering with the pursuit of a solution till success, illustrating a high level of self-efficacy.

In terms of RQ1**,** *How do A-level physics students in an inner London comprehensive school approach physics problem solving?,* the student shows inadequate metacognitive processing in orientating and planning, as evidenced by the repetitive reading. There is no explicit data extraction to reduce cognitive load, no modelling of the given scenario or any evidence that shows a reduction of the problem to a visual form wherever possible. Developing problem-solving proficiency is hampered by low collaborative competencies leading to a failure to create a JPS. The student demonstrates excellent mathematical procedures and progresses quickly despite a lack of logical progression. The high self-efficacy demonstrated in this problem-solving session leads to a high level of perseverance when solving the context-rich problem.

A. Second cycle

Data for this cycle is found in appendix 6

i. Metacognitive competencies

As part of understanding the problem demands the student reads the problem repeatedly without explicitly noting down the problem conditions or explicitly extracting the data. This inadequate *orientating* results in the repeated re-reading of the problem conditions. As part of the *planning*, the student underlines key facts and plans the solution before writing the final draft. Once the solution path has been planned, *execution* follows. During the course of the problem-solving process, regular *monitoring* of problem comprehension is evidenced by periodic re-reading of the problem statement and checking the solution process. *Monitoring* becomes more regular with an increase in problem difficulty. The student evaluates his knowledge state against the problem state (08:30 and 09:00). In addition, there are instances where calculations are evaluated before proceeding (12:00 and 12:30). The extract (table 4.12) illustrates the discussed regularities.

07:30	Moves to next question. Reads question slowly " ... *ahhh* ..."
08:30	*"... Ok so the power dissipated is ...P= I squared R ... we need to work out the value for R which is V/I* **...**"
09:00	Reads on "... *justify that the maximum is at or near point B ..."* underlines the word justify.
	"... *I am not sure what I am about to do* ... " Keeps reading for comprehension and cues.
10:00	Writes down P = I^2R.
	"... *ok .. I have to take values for those points. At point A, I equals to 0.35A, R equals to ...* "... searches the graph for more data and picks a calculator, calculates R. **Good breakthrough and perseverance indicating high self-efficacy.**

Table 4.12: Extract of a verbalisation illustrating a working forward strategy with metacognitive self prompts

ii. Cognitive competencies

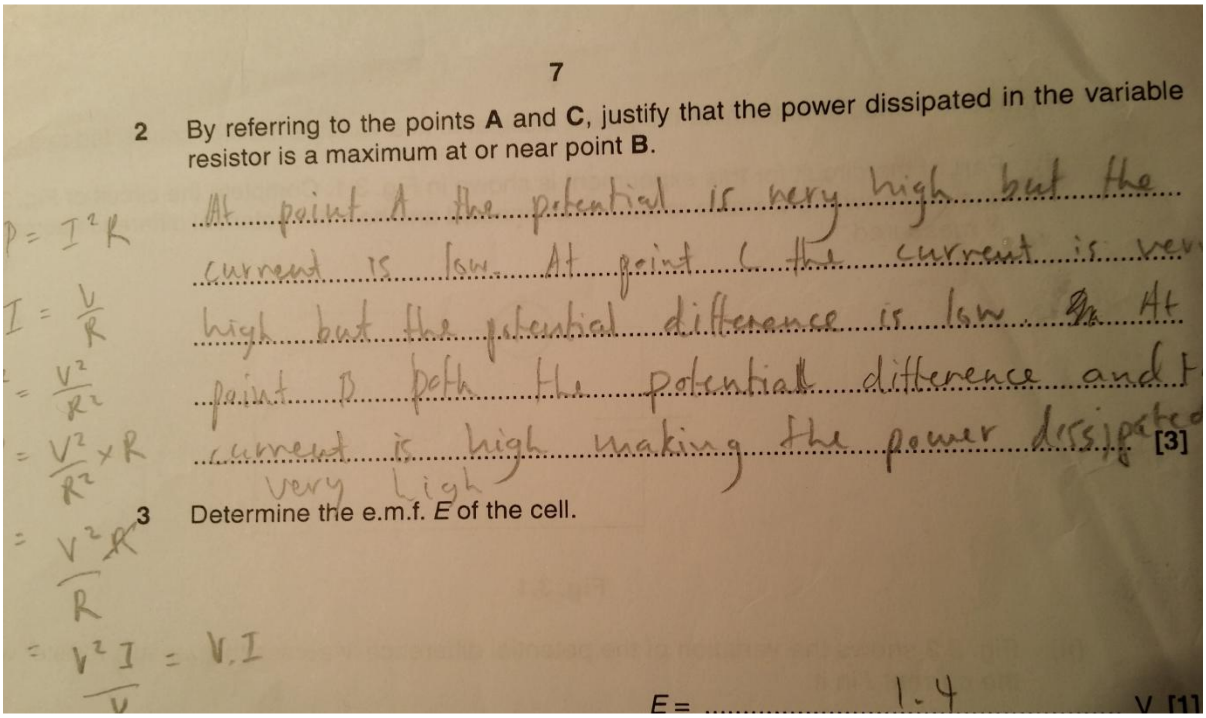
As part of the *useful description* stage, the student underlines key points. Fundamental equations are noted as part of the *planning* and *appropriate physics* concepts and equations are noted, successfully converting them to specific equations for the context. The progress from planning to *physics approach* and application of physics forms one continuous step. There is a clear working forward strategy as the student progresses from establishing the problem demands to choosing appropriate physics and proceeding to a solution. The student extends beyond basic *mathematical procedures* of algebraic manipulations to mathematical representation of the scenario using simultaneous equations, a novel approach!

There is a clear and consistent *logical progression* as the student progresses from the problem statement to physics equations, where required, terminating in a reasonable solution. Specific physics concepts are used to explore and explain causal links (table 4.13). As compared to the first cycle where the student progresses through a trial-and-error strategy, there is clear planning leading to a good logical progression.

02:30	Re-reads question again, underlining key points.
03:00	" ... *Internal resistance* **...** *so .. . if you change* ..." Does a mental analysis.
03:30	"*... therefore...*" ... "*... so V = I(R+r) ... emf is constant ...if the resistance of the resistor goes down, therefore current will go up..therefore it means the terminal pd will decrease ...* "

Table 4.13: Extract to show causal exploration QL-AN problems.

There is a clear exploration of causal links (03:30). The excerpt from the student's protocol illustrates this logical progression in solving qualitative analytical problems (figure 4.6).



7

2 By referring to the points **A** and **C**, justify that the power dissipated in the variable resistor is a maximum at or near point **B**.

At point A the potential is very high but the
current is low. At point C the current is ver
high but the potential difference is low. ~~In~~ At
point B both the potential difference and t
current is high making the power dissipate
very high

[3]

$P = I^2R$

$I = \frac{V}{R}$

$= \frac{V^2}{R^2}$

$= \frac{V^2}{R^2} \times R$

$= \frac{V^2\cancel{R}}{R}$

$= \frac{V^2 I}{V} = V.I$

3 Determine the e.m.f. *E* of the cell.

E = 1.4 V [1]

Figure 4.6: Working on the left shows planning to show causal links for a qualitative analytical problem

iii. The student demonstrates a high *self-efficacy* as illustrated by the progression. Despite being unsure of the next step and not comprehending the problem fully, the student perseveres with the problem (03:00; 10:00 and 12:30). The following extract illustrates this observed regularity, indicating high self-efficacy. The result is a correct justification.

09:00	Reads on "... *justify that the maximum is at or near point B ...*" underlines the word justify.
	"... *I am not sure what I am about to do* ... " Keeps reading for comprehension and cues.

Table 4.14: Extract to show persistence as evidence of high self-efficacy.

Summarily, these data show a shift in metacognitive processing. As part of the orientating phase, the student underlines key facts and plans the solution before writing the final draft. There is evidence of increased purposeful monitoring through slow re-reading of the problem statement and checking the solution process. The monitoring becomes more regular with an increase in problem difficulty. There are instances where calculations are evaluated before proceeding. However, the planning is not exhaustive as the student continues to read the problem repeatedly without explicitly noting down the problem conditions or explicitly extracting the data. A clear working forward strategy is adopted as the student progresses from establishing the problem demands to choosing appropriate physics and proceeding to solution. The student extends beyond basic mathematical procedures.

A clear strategy on solving qualitative analytical problems is evidenced by initial planning and exploration of causal links using specific physics concepts consistent with the concepts. This shift is buttressed by evidence from the G482 external examinations where the student´s performance improves from 52% to 81% (figure 4.7)

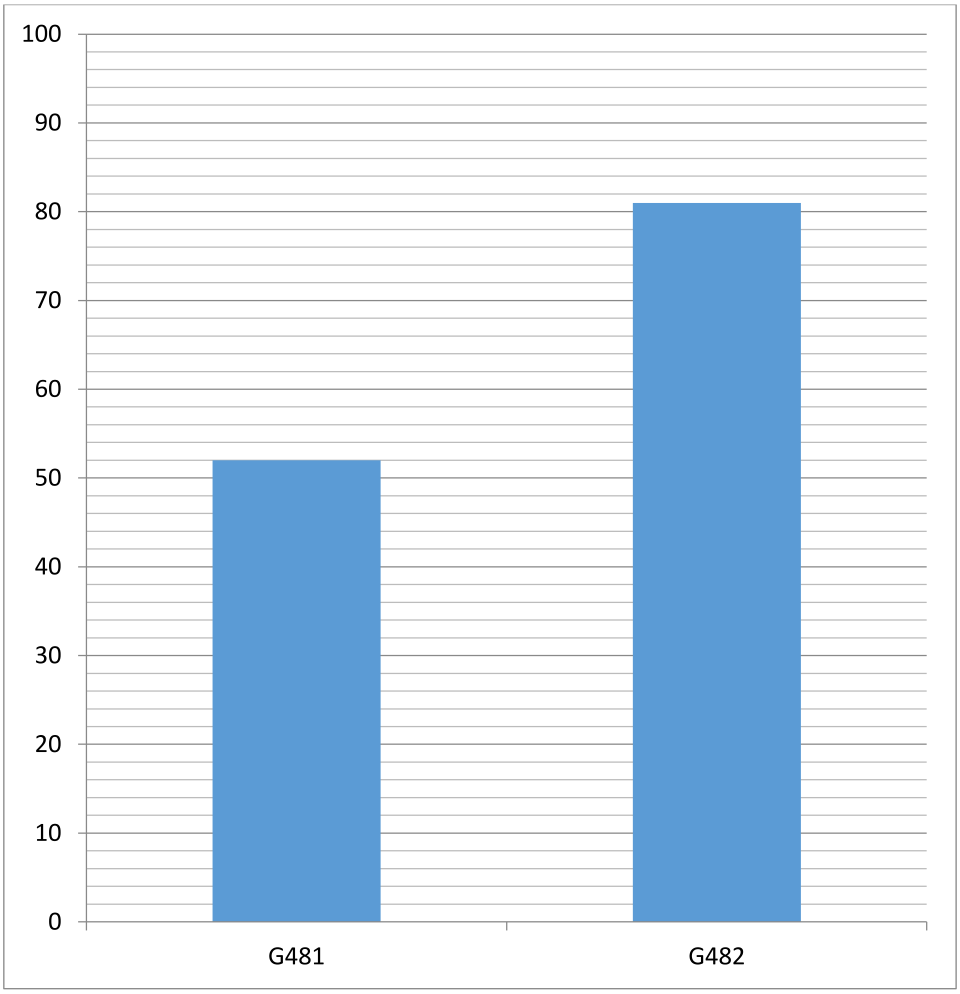
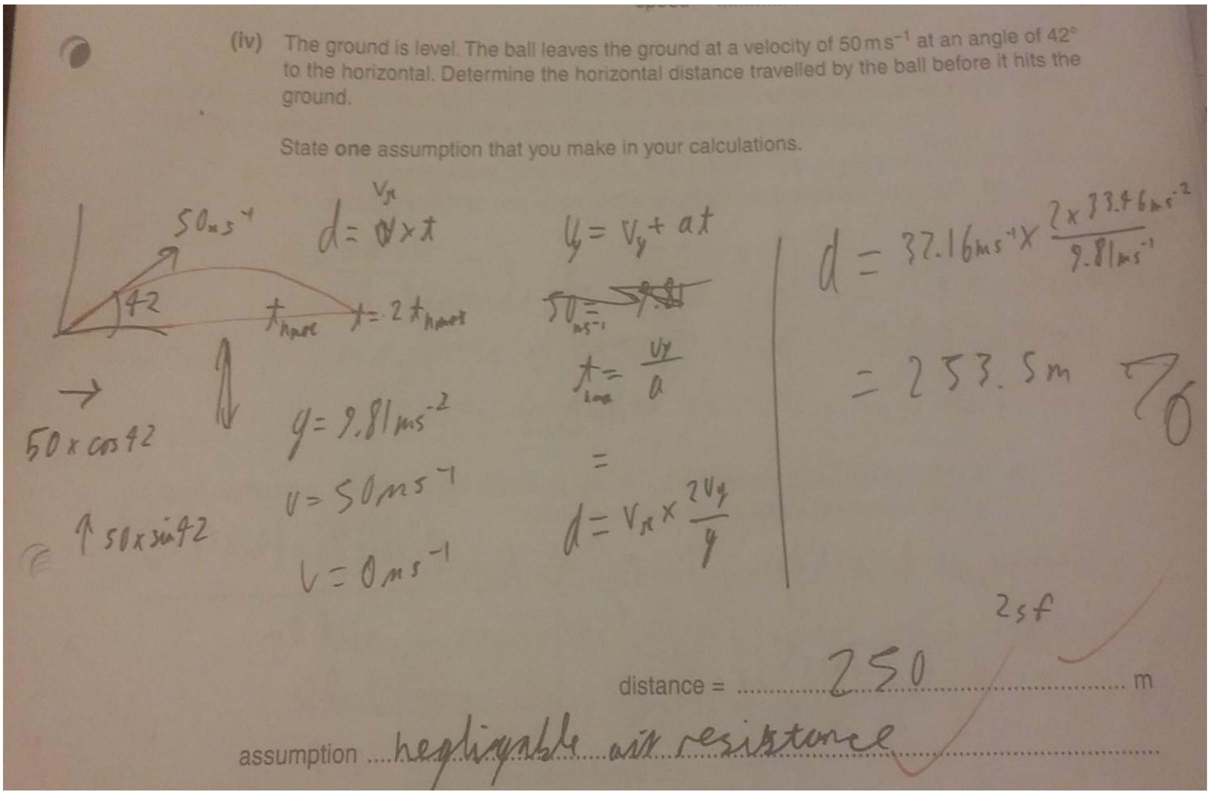


Figure 4.7: Evidence of progress for Jamal by the end of the first intervention cycle (G481 vs G482)

B. Exit data

i. Metacognitive Competencies

The exit task consisted of problems from past examinations papers so as to simulate examination conditions. The student adopts a novel approach, assessing his current knowledge state relative to the whole task. Task-specific self-efficacy is assessed for each task using confidence rating scales. The problems with the highest confidence rating are solved first. A forward working strategy is adopted with the use of a heuristic. The extract from the solution script demonstrates the use of a heuristic where the student extracts data explicitly models the scenario, writes down specific equations for the problem conditions and proceeds to substitution. Cancelled work shows evidence of monitoring. The ‘70’ (bottom right) shows the confidence rating. The 70% rating is matched by the level of success in solving the problem.



(iv) The ground is level. The ball leaves the ground at a velocity of 50 m s^{-1} at an angle of 42° to the horizontal. Determine the horizontal distance travelled by the ball before it hits the ground.

State **one** assumption that you make in your calculations.

distance = 250 m

assumption negligable air resistance

Figure 4.8: A clear heuristic with evidence of monitoring and self-efficacy

There is evidence of a thorough *orientating* stage, followed by planning as illustrated by a well-structured plan which is relevant to the task. The overt orientating and planning actions include reading and re-reading the problem statement followed by data extraction and modelling. *Execution* follows planning with algebraic manipulation of specific equations using physics relations in the form of equations. There is regular monitoring of the execution process. Mathematical substitution is carried out last. There is regular *monitoring* of comprehension of the problem statement and progress of the problem solving process. The student progresses through metacognitive self-questioning e.g. ... *are that´s all right**...**?* ... *What other equation do I know for this …?* (See table 4.15).

3:00	“... *is that all right* ***...****yeah*.. so T is equals to 2 pi times R..T is equals to ... ”
04:30	“... *that’s 10.9* **...”** writes answer down and scans working again.
07:00	Stops to check answer and continues to write.
08:30	“ ... *ok that’s it...next one* **...** ”
	“... *now in this situation a =? therefore we could say GM/R=a/R...can we say* *a= GM?...ummm ...* ”
10:30	The student pauses.
	Monitoring results in change in approach through reviewing the equation.
11:00	Student pauses and sighs (realises the difficulty of this problem).
	“... ummm I forget all about centripetal force ...” Erases the equation $v^2 = a/R$. Looks at the problem.
11:30	
12:00	“... *What other equation do I know for this? ...ok F = GMm/R^2 …*” **A good metacognitive question**! **Monitoring results in change in equation and breakthrough**.

Table 4.15: Metacognitive self-prompts and purposeful monitoring

Monitoring goes beyond basic checking of progress and comprehension, resulting in a change in the solution path (10:30 -12:00). Guided by metacognitive self-prompts, the student realises the increased level in difficulty and searches for further equations, resulting in a breakthrough. The student initiates the task by *evaluating* his current knowledge state against the tasks. Solutions are evaluated before proceeding to the next problem (08:30).

i. Cognitive Competencies

The *useful description* stage begins with an initial exploration of the problem, culminating in the explicit data extraction. There is a clear physics approach as relevant equations are noted, with the solver adopting a working forward strategy. However, there is limited visual representation of the problem; there is neither full use of models nor annotation of the diagrams to show full exploration of the problem. Despite the lack of modelling, *specific application of physics* is good as appropriate equations are employed correctly for the problem´s specific conditions. In addition, the student derives equations from first principles when in doubt.

11:30	*"... ummm I forget all about centripetal force ..."* Erases the equation $v^2 = a/R$. Looks at the problem.
12:00	*" ... what other equation do I know for this? ... ok* $F = GMm/R^2$ ..." **Monitoring results in change in equation and breakthrough**.
12:30	*"... the force is* $mg = GM/R^2$*, so* $g = GM/R^2$*... ok ... that´s it ..."*

Table 4.16: A deep analysis of the scenario based on fundamental concepts

A working backwards strategy was also adopted to verify the value of the universal gravitational constant (data booklet had not been provided). The problem-solving process shows excellent mathematical procedures. There is a clear and consistent progress from problem statement to the answer. The student also demonstrates that they can deviate to other solution paths.

ii. Self-efficacy:

The student progresses well and scores high marks consistent with the high confident ratings. After monitoring and noting an uncertainty in the equations the student derives these from fundamental concepts.

Summarily, the intervention process produced a shift in this able student. There is a deliberate well-planned deployment of strategies aimed at reducing cognitive load through use of models and extracting data. The student use heuristics in solving quantitative problems that require calculations, i.e. they study the problem, extract the data, model the problem, establishing relations between quantities for the specific scenarios in the form of equations and the substitution of data in the final equations. For problems that need a qualitative analysis, there is a planning phase which includes modelling of the problem as diagrams, graphs or another visual form. The student further establishes the physics relations in the form of equations to buttress the argument, exploring causal links and then converting a rough draft of the solution into a logically sequenced solution.

There is a significant reduction in error rates as evidenced by a considerable increase in metacognitive monitoring and more time spent on qualitative analysis of the problem. For familiar problems and processes like algebraic manipulation, there is evidence of automation, suggesting development of schema. The external G481 GCE physics exam (OCR-A) was in January 2013, the intervention started in March 2014. In July 2014 the student improved from 65% to 81% in the G482 June exam. In comparison to the G481, the G482 exam is considered more difficult since it covers a wide range of concepts, with the questions demanding a solid base of scientific knowledge. By the end of the project in October 2014 the student had demonstrated a marked improvement in tackling qualitative analytical problems, an area identified as in need of improvements from the entry data.

Exit data from CGPS show a high level of collaboration as Jamal initiates the establishment of the JPS. Each group member has to rate their self-efficacy for each problem before attempting the task. *Promotive interaction* is further shown when the student engages in collaborative argument with Nikolai on the applications of resonance. In monitoring group progress Jamal suggests a checklist of all the problems successfully solved in order of confidence rating and completion. The extract (table 4:17) illustrates instances of high collaboration during the exit CGPS from Jamal and the other group members.

COLLABORATION	**Positive interdependence** Student assumes different roles but mainly acts as a facilitator, facilitating group interactions and managing group progress. The student focuses on performance optimisation, suggesting to the group to do confidence ratings and then starting with those problems with high confidence ratings. **J** *“ … right , give me all the confidence ratings and I will order them … ”*

	Promotive interaction Student suggests verifying the group efficacy before attempting the task. Engages in collaborative argument with Nikolai on the applications of resonance (05:00). Suggests a checklist of all the problems in order of confidence rating and completion (07:30). Engages in repair and the joint construction of the solution (10:00-11:30).
	Individual accountability Student initiates enquiries about the abilities of team members and assumes different roles. Suggests and enacts plans with group members. Identifies efficient ways to optimise attainment within the given time. Takes the initiative to perform and check mathematical operations within the group.
	Group processing Initiates the task by enquiring each group member`s confidence rating to build group efficacy. Uses conceptual knowledge to evaluate others contributions. Evaluates the collective success of the group. 18:00. Group discusses time left, J checks progress; N & M check the calculations. **J** "…. we have done ..." **lists the problems solved so far**. **J & S discuss next task.** Jamal participates in repairing shared understanding and joint construction of solution. **S** "..Isn't K that?" **points at graph.** **J** ".. that's not, that's potential , it's opposite that … " **S " …** oh yeah, it's a sketch graph … "

Table 4.17: Summary of collaborative competences for Jamal

However, there is evidence of inadequate modelling of the problem, inadequate *orientating* and *planning*. The diagrams are not annotated nor models constructed for problem representation table 4.17. However, apparently with this 'frugal' modelling the student successfully solves the problem. A plausible explanation is that if the student has internalised most of the strategies and built a robust schema then most of the stages are skipped.

4.5.2 *Findings for Mik*

A. Entry data

i. *Metacognitive Competencies*

Mik spends considerable time on *orientating* and monitoring comprehension through repeated reading. The task is finished after 27 minutes instead of the 15 minutes allocated. There is evidence of lack of comprehension-enhancing strategies like metacognitive prompts when reading. As part of the planning, the student models the problem but further progress is hampered by poor question comprehension and inadequate scientific knowledge. There is no use of equations to explore causal links when solving qualitative analytical problems. The failure to link the model to the problem demands suggests an inadequate problem-solving schema.

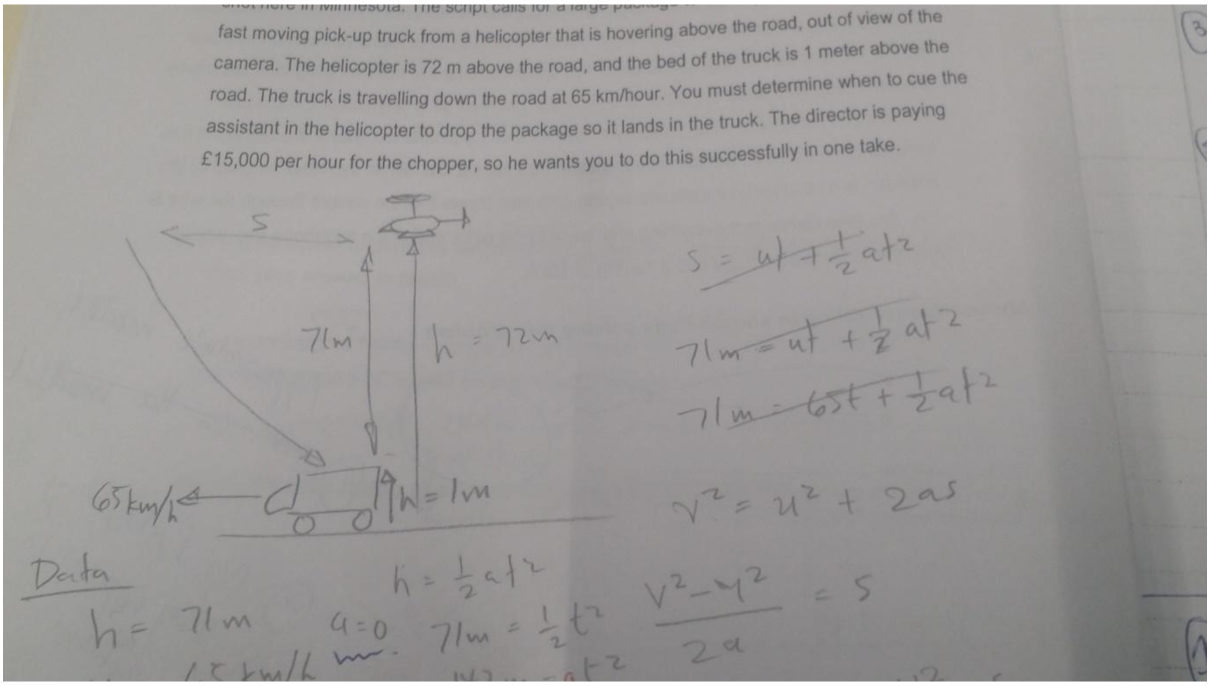
The *execution* step is not consistent with the initial plan. The student progresses through a trial-and-error approach, weaving between all three problems. At 08:00 the students attempts problem 2 and abandons it at 10:00, then attempts problem 3. Before completing problem 3, the student moves back to problem 1 (15:00). At 17:00 he moves back to question 2 and eventually completes it. At 23:00 the student embarks on problem 3. Monitoring of knowledge is regular but not focussed on progress, as indicated by the whole task lasting 27 minutes. Monitoring leads to change in the direction of progress (06:00, 14:30 and 16:00) or the decision to move to another task and allow for incubation time. As the problem solving proceeds, the student evaluates proposed solutions against problem requirements.

25:30	*"... if we use $v^2 = u^2 + 2as$ ..."* Reads again**. A trial-and-error approach.**
26:00	*"... Shall we use projectile motion ... the range is equal to R =V x .t ... "*
26:30	Writes a series of equations ... $h = 1/2\ at^2$ ... a= 0.
27:00	Scans answer and rates success confidence at 60 %.

Table 4.18: Evaluation of specific physics concepts

ii. Cognitive Competences

As part of the initial *useful description*, the initial qualitative analysis involves explicit data extraction and modelling. However, there is no clear link of the data or model to the following steps. The student is not clear on the physics concepts to apply as evidenced by the number of equations crossed out. Evidently the student adopts a trial-and-error strategy. The *physics approach* and *specific application of physics* are therefore insufficient due to an incomplete conceptual understanding of the problem (figure 4.9).



Minnesota. The script calls for a large

fast moving pick-up truck from a helicopter that is hovering above the road, out of view of the camera. The helicopter is 72 m above the road, and the bed of the truck is 1 meter above the road. The truck is travelling down the road at 65 km/hour. You must determine when to cue the assistant in the helicopter to drop the package so it lands in the truck. The director is paying £15,000 per hour for the chopper, so he wants you to do this successfully in one take.

Figure 4.9: Good problem modelling with inaccurate specific physics

Through trial and error, the student progresses to the solution, as evidenced by the extract in table 4.19 The student is not clear on independent vertical and horizontal motion in projectiles which should have been explicitly stated in the equations. Other issues which contributed to lower marks can be attributed to the lack of a schema for solving context-rich problems.

25:30	*"...if we use $v^2 = u^2 + 2as$ ..."* Reads again**. A trial and error approach.**
26:00	*"... Shall we use projectile motion?* the range is equal to R =V x .t ... "

Table 4.19: A breakthrough using a trial and error strategy

The student timely and correctly substitutes the data into the equations, demonstrating competent mathematical procedures. The problem-solving process is slow with no clear *logical progression*. The student shifts from one problem perceived to be difficult to another. The final solution goes beyond a numerical answer, e.g. problem 2 where the distance must be given with reference to a point. There is no clear evaluation of the solution in view of the problem demands.

Data from the G481 examination scripts revealed good progress with problems that could be solved with the basic heuristic (*data* → *equations* → *substitution* → *solution*). However, the use of this heuristic is inconsistent as there are instances where data are not extracted explicitly. Problems that require an in-depth causal analysis are not solved and attainment on qualitative analytical problems is low. There is poor time management and low self-efficacy in certain domain areas as evidenced by unsolved problems with a total of nine out of 15 marks.

iii. Self-efficacy

The student shows high self-efficacy in some areas as he perseveres with the hard problems for 27 minutes scoring 60 % of the marks. The self-rating confidence for the task ranges from 60% to 80% with the highest rating on the routine problem. However, evidence of unattempted problems reveals low self-efficacy.

iv. Collaboration

Mik infrequently participates in the CGPS unless prompted. There is little participation in establishing the joint problem space or in the collective exploration of the problem and Mik contributes only when prompted to evaluate a suggestion or a completed stage. This reduced promotive interaction to facilitate a joint co-construction of the solution leads to low positive interdependence. Except for a few occasions of monitoring when Mik checks the solutions (02:00, 06:00), the partner assumes the role of scribe and manager and independently solves the problems. Summarily, Mik demonstrates low collaborative competences.

B. End of cycle 1

i. Metacognitive competencies

In the *orientating* phase, there is purposeful exploration as Mik reads the question, repeats it slowly and then proceeds to make a plan. As an example, with a momentum problem, the planning includes data extraction, drawing a reference frame and using equations to explore causal links for qualitative questions. *Execution* follows from the planning with monitoring as the student assesses his knowledge and corrects this execution process. The student pauses and checks progress and consequently, at 07:30, this results in a change in direction of the problem-solving process. Evidence from the script shows some corrected work, evidence of a monitoring process. Table 4.20 shows evidence of the observed consistent and timely monitoring of the problem-solving process (07:30 - 08:30).

02:00	Moves to question 1(b).
	"... *so I choose that direction to be positive* ..." draws reference line and assigns a positive direction.
02:30	"*... The data is ….the M_A is 3.0 kg* **..**" proceeds with data extraction . **Deploys a heuristic approach for momentum and collision problems.**
07:30	"*... so impulse is m x a x* t **...** "
	Pause and checks.
08:00	" ... we don't have acceleration , so we can't use this ... "
	"*... ΔP is equal to mV-mU … so to find the final momentum ...* "

Table 4.20: Monitoring during problem solving

Evaluation can be inferred from the instances where the student checks a stage and moves on. This can be interpreted as confidence in the solution since the student does not return to check the solution. There is no clear testing of the solution using another approach to verify the solution.

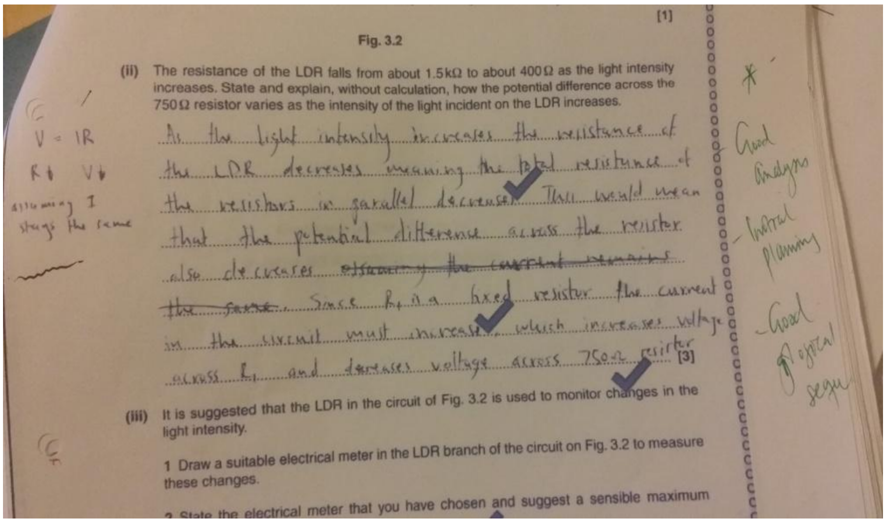
ii. Cognitive Competences

The initial exploration involves extraction of the data and designating quantities as per problem state, e.g. M_A =3.0 kg, evidence of good *useful description* of the problem. The degree of accuracy is even specified in the data. There is identification of the key aspects of the problem and underlining of key data, e.g. ... common velocity ... and the interpretation in the data $V_A = V_B = V$. The assumption of a reference frame is highlighted as part of the planning. The student deviates from the adopted strategy (07:30).

The approach to answering qualitative analytical questions lacks rigour as the student drops the use of models which would have allowed for an in-depth analysis of the problem. There is a good understanding of the physics problem as the equations chosen are converted to reflect the specific context. The final quantities to be calculated are made the subject of the formula before the substitution process.

Evidence shows an accurate selection of appropriate mathematical procedures with the use of correct equations and correct mathematical steps. There is a clear flow towards the solution with all steps, algebraic manipulations and degree of accuracy clearly shown. The solution shows a consistent progress from the problem statement to the specific physics equations, terminating in a reasonable answer. The student demonstrates that they can repair understanding when stuck. Explanations are backed up with the correct science, e.g. explaining impulse on colliding objects using Newton’s laws.

Despite a lower overall attainment in G482, the student demonstrated an improved approach to solving higher order problems (QL-AN). Time management and schema building were areas of weakness that still needed attention.



[1]

Fig. 3.2

(ii) The resistance of the LDR falls from about 1.5kΩ to about 400Ω as the light intensity increases. State and explain, without calculation, how the potential difference across the 750Ω resistor varies as the intensity of the light incident on the LDR increases.

As the light intensity increases the resistance of the LDR decreases meaning the total resistance of the resistors in parallel decrease. This would mean that the potential difference across the resistor also decreases ~~assuming the current remains the same~~. Since R_1 is a fixed resistor the current in the circuit must increase which increases voltage across R_1 and decreases voltage across 750Ω resistor [3]

$V = IR$

$R\downarrow$ $V\downarrow$

assuming I stays the same

Good Analysis

Initial planning

Good logical sequ

(iii) It is suggested that the LDR in the circuit of Fig. 3.2 is used to monitor changes in the light intensity.

1 Draw a suitable electrical meter in the LDR branch of the circuit on Fig. 3.2 to measure these changes.

2 State the electrical meter that you have chosen and suggest a sensible maximum

Figure 4.10: Causal exploration and planning for QL-AN problems

iii. Self-efficacy

The smooth progression with mostly a working forward approach can be interpreted as manifesting a high level of self-efficacy. In most cases the student orientates, plans and executes with little difficulty, suggesting existence of schemata. The student persists with the problem after realising that the chosen solution path was not consistent with the problem conditions.

Summarily, this cycle shows a clear initial exploration of the problem, albeit cases where the student does not model the problem. Key data are highlighted and specific physics concepts are applied without a trial-and-error approach. There is a clear logical progression from the problem statement to the solution. In addition to a clearer orientating phase, there is a shift in the deployment of metacognitive processes throughout the process. The student pauses and checks progress when necessary. Corrected solution steps from the G481 examination script provide evidence of monitoring which results in a shift in the direction of the solution path. The G482 module reveals a marked drop in marks for quantitative and graphical problems (figure 4.11). A total of 27 marks worth of problems were not attempted. However, the student showed a marked improvement in solving qualitative and analytical problems in the G482 examination. Overall attainment drops from 63% to 58%, whilst the unsolved problems were worth 27% of the total marks. This can be argued as evidence of an improvement in the quality of the problem-solving process.

A possible explanation for the loss of these 27 marks could be inadequate problem-solving schemata on the rather more difficult G482 course. Problems with time management still persist. These areas were some of the main areas of focus in the second action research cycle.

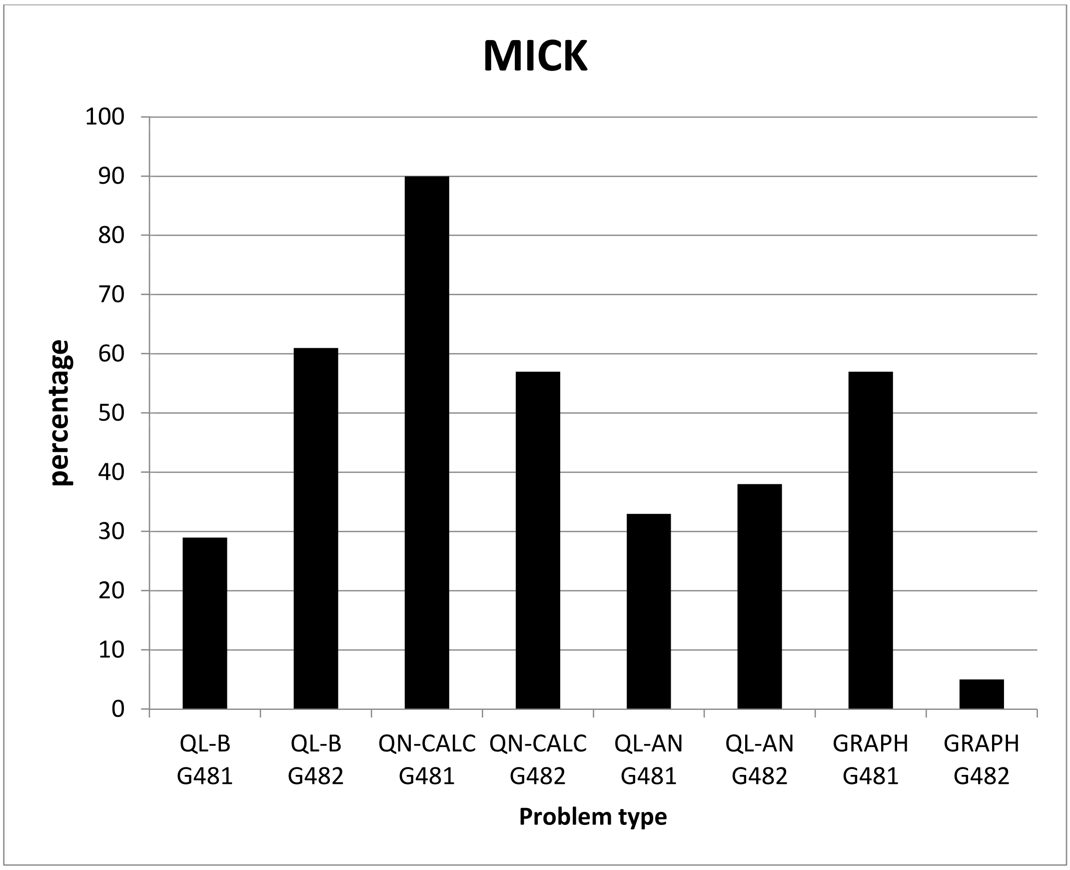


Figure 4.11: Comparison of performance in G481 and G482 for Mik

C. End of cycle 2: Exit

i. Metacognitive competences

A shift in approach to the orientating step occurs as the student assesses his confidence in successfully completing each of the problems (table 4.21). This approach helps with time management and was emphasised during the second cycle. This phase of planning involves picking relevant cues and possibly linking them to already existing schemata and evaluating the success of the transfer process for the novel situation.

00: 00	*“... I will start by doing my confidence ratings … ”*

00:30	*“… I will give this 90 ... ”*
	Flips through *“… question 2… ok … ”* scans the question . *“... it’s about circular motion and little on gravitation ... ”*
01:00	*“ … It’s just this one page. So will give that 90 …”* Flips through the pages, scanning the questions.
01:30	*“… then question 5 is about thermal physics …and it’s a lot more qualitative ...so give that 70 ... ”*
02:00	Moves back to first problem, rated 90. *“… State the principle of conservation of linear momentum …”* reads question slowly.

Table 4.21: Assessing self-efficacy as part of the initial problem exploration by Mik

The *planning* phase includes data extraction, drawing models and using equations to explore causal links for qualitative questions. In problems that require far transfer, e.g. problem 1 (b), the student uses a working forward heuristic strategy. There is a step-by-step modelling of the scenario and correct application of physics (table 4.22).

08:30	*“…. so first get down the data, radius of the circle is 5 meters, speed of the air going downwards is 12ms*$^{-1}$ *…. ”* Proceeds to extract data.
09:00	Finishes and reads question again.
	“... they say the descending air occupies a cylinder, a cylinder has a radius of … ”
09:30	Models the cylinder by drawing.
	“... so if the density, which is mass/ volume … so what we should do is find the volume of the cylinder and multiply by the density to get the mass … ”
	“... and here the metres will just cancel out and will remain with kilograms ...” **Good use of units to monitor accuracy of algebraic manipulation.**
11:00	Pauses and checks work.
	“... so πR^2 *will give you the circle …the height will be 60 m…”* corrects the initial value on the mode …” **Use of a working backward strategy and the good monitoring of work results in change in data.**

Table 4.22: Verbalisations indicating a working forward approach by Mik.

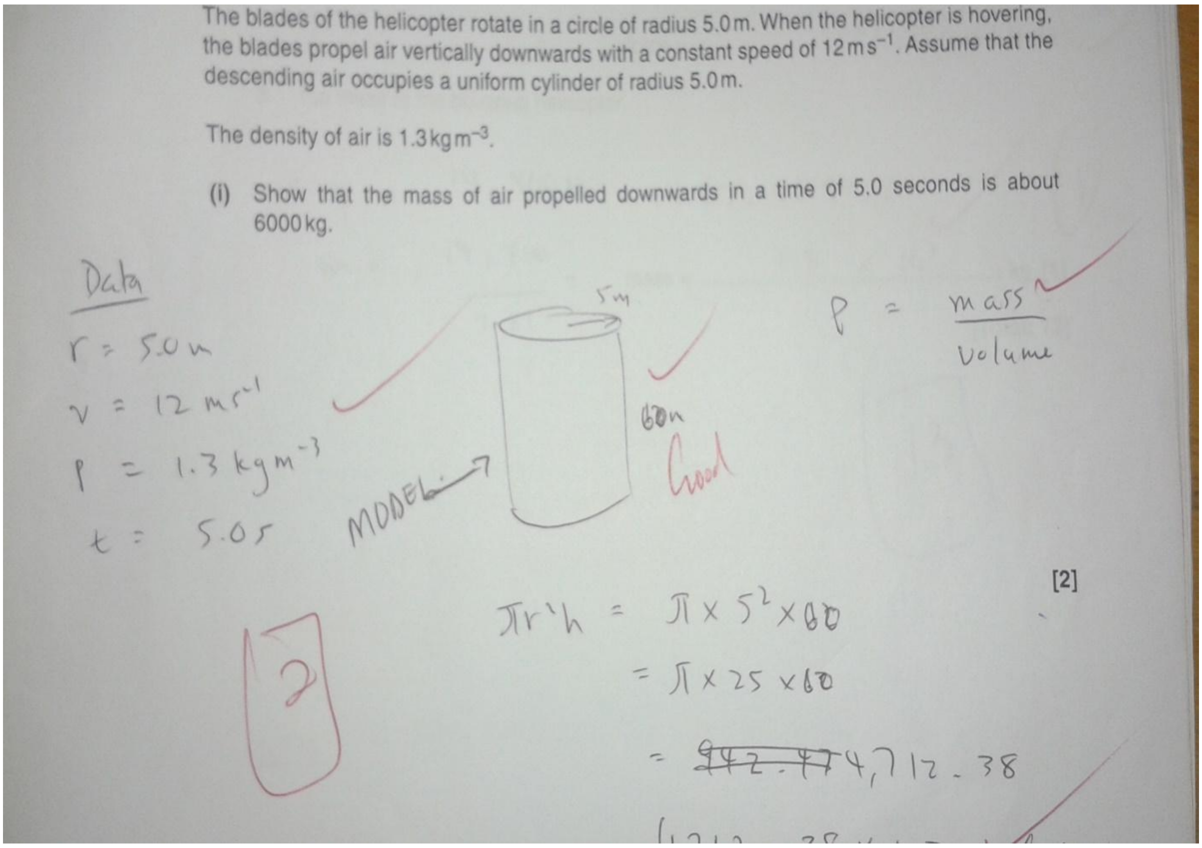
Execution follows from the planning, simultaneously with monitoring. There is consistent monitoring of the problem-solving process with regular monitoring for the higher demand problems. For routine problems there is less monitoring, suggesting existence of a valid schema and high self-efficacy. There is little evaluation of the solutions but a high success rate for this task (27/30), suggesting a high self-efficacy.

ii. Cognitive competences

The *useful description* competence is characterised by a thorough initial analysis of the problems including rating the probability of success for each problem. Information is organised through data extraction and construction of models. The domain of each problem is identified and the fundamental relations stated as part of the initial exploration. Physics concepts are well selected and there is a clear strategy that involves modelling (figure 4.12). There is an improvement in rigour when solving qualitative analytical problems. The modelling is supported by accurate physics concepts that link to the problem statement. There is a good understanding of the problem as the equations chosen are converted to reflect the specific context. The final quantities to be calculated are made subject of the formula before the substitution process. The verbalisations demonstrate a clear understanding of the physics concepts to be applied (table 4.23).

07:30	*".. . Equal to 10.8 J and final kinetic energy is …"* Calculates values "... you only got 2.13 J ... "
	"... so final kinetic energy is 2.13 J which is not the same as the initial KE **…** *"* writes *10.8 J is not equal to 2.13 J*
08:00	*"... energy is lost and collision is inelastic …"*
12:00	Reads part (ii) *"... Calculate momentum …"*
	"… So momentum is equal to m x V , the mass of air is 600 kg and the velocity is 12ms^{-1} *…so multiply 6126 by 12 ... "* Calculates *"… that's 72 000 kgms*$^{-1}$ *…7.2 x 10*^{4} *..."*
13:00	*"... calculate the force provided by the rotor …" "… so Newton's Second Law ….*$F=\Delta P/\Delta t$*…. so* Δt *is 5 seconds ... "*
13:30	Calculates the values "*...that's 14 400 N ... "*

Table 4.23: Verbalisation to show a clear understanding of the specific physics by Mik.



The blades of the helicopter rotate in a circle of radius 5.0 m. When the helicopter is hovering, the blades propel air vertically downwards with a constant speed of $12\,m\,s^{-1}$. Assume that the descending air occupies a uniform cylinder of radius 5.0 m.

The density of air is $1.3\,kg\,m^{-3}$.

(i) Show that the mass of air propelled downwards in a time of 5.0 seconds is about 6000 kg.

[2]

Data

$r = 5.0\,m$

$v = 12\,ms^{-1}$

$\rho = 1.3\,kgm^{-3}$

$t = 5.0\,s$

MODEL

5 m

60 m

Good

$\rho = \frac{mass}{volume}$

$\pi r^2 h = \pi \times 5^2 \times 60$

$= \pi \times 25 \times 60$

$= \cancel{942.477}\ 4,712.38$

2

Figure 4.12: Modelling strategy in planning - Mik

Mathematical procedures are well executed through the use of correct equations and correct mathematical steps. There is a clear flow towards the solution with all steps, algebraic manipulations and degree of accuracy clearly shown. Mathematical manipulations are also used to dimensionally check the consistency of the solution with the physics quantity to be calculated (table 4.24).

10:30	Mik substitutes data to calculate the volume.
	"... and here the metres will just cancel out and will remain with kilograms ..."

Table 4.24: Evaluation of solution through dimensional analysis – Mik

There is a clear *logical progression* of the *problem-solving process,* from the problem statement to the specific physics equations, terminating in a reasonable answer. The student demonstrated that they can repair understanding when stuck. Figure 4.12 shows corrected working and data on the model.

iii. Self-efficacy

The student allocates high confidence ratings for the two problems solved (90%), further confirmed by the high level of success in the task. There is a rapid and accurate progression of the problem-solving process with less monitoring. This reflects a high self-efficacy.

iv. Collaboration

During CGPS, Mik participates collaboratively, with a clear coordination of language and action through specific turn taking.

01:00	Jamal reads question 1
	Sue. “… kinetic energy is not conserved … “
	Mik. “ … yeah that means momentum is conserved … ”

Table 4.25: Specific turn taking during CGPS

There is good promotive interaction as the student participates in the construction of the JPS and in repairing shared meaning by establishing a joint understanding of the problem state (table 4.25).

03:00	Jamal. “ …. I think that’s over 70%, 80% … ”
	Mik. “… I will give that 70% …” Sue. “...yeah that´s 70% ... ”
16:30	Mik “... and it must include mass ... ”
17:00	Mik re-reads the problem “... aah ... they give kinetic energy ….”

Table 4.26: Repairing shared understanding during CGPS.

The student enacts the agreed strategy by contributing to assessing group efficacy. On analysing the question on simple harmonic motion he observes that the group had not considered the fact that kinetic energy is provided. Mik assumes various roles within the established joint problem space. He proposes and critically evaluates group member inputs with the respect to the problem state. He participates in establishing the joint problem space and building the group efficacy. There is regular monitoring of the solution path and proposing changes. The excerpt, table 4.27, shows an exchange between Mik and the scribe (Nik) on evaluation of the written solution.

12:00	Jamal. **calculates** " … 0.6 … " Nik. " … Mik, check if the answer is reasonable … "
12:30	Mik checks the working and nods. Mik. " ... ok next question … "

Table 4.27: Assuming the role of group critic by Mik.

The verbalisations, the actions and level of attainment show a shift in cognitive-metacognitive processing and collaborative competences in this student. Mik adopts a purposeful exploration of the problem, a shift from the trial-and-error approach at the start of the first cycle. Self-efficacy remains high. Clear verbalisations, e.g. "... *So I choose that direction to be positive* ..." show the adoption of a working forward strategy (table 4.28). By the end of the intervention, the *orientating* stage involves the student assessing the whole task by identifying the domain for each problem and then assessing his confidence. Examples of verbalisations include *"... I will start by doing my confidence ratings …" and "… I will give this 90 ..."* Further evidence of this shift is seen in how Mik solves qualitative problems where he uses equations to explore causal links.

08:30	*"… so first get down the data, radius of the circle is 5 meters, speed of the air going downwards is 12ms^{-1} ... ."*
09:30	*"... They say the descending air occupies a cylinder, a cylinder has a radius of …"* Models the cylinder.

Table 4.28: Verbalisations top show a working forward strategy – Mik.

From the entry videos, the *execution* follows no plan. The student weaves between all three questions through trial and error. At 08:00 the students attempts problem 2 and abandons it at 10:00 to attempt problem 3. Before finishing problem 3 the student moves back to problem 1 (15:00). At 17:00 he moves back to question 2 and eventually completes it. A problem that required 15 minutes was completed in 27 minutes. By the end of the first cycle, the *execution* follows from the plan and orientation. Between 07:00 and 08:30 the student assesses his knowledge and corrects his execution process (table 4.29).

07:30	*“... So impulse is m x a x* t **...”** Pauses and checks.
08:00	“ ... we don’t have acceleration , so we can’t use this ... ”
	“... ΔP is equal to mV- mU... so to find the final momentum ... ”
	“... and here the metres will just cancel out and will remain with kilograms ...”
11:00	Pauses and checks the work.
	“... so πr^2 will give you the circle ... the height will be 60 m ... ” Corrects the initial value on the model.

Table 4.29: Monitoring before execution leading to a change in the solution path – Mik.

Exit video data highlight the possibility of simultaneous execution and monitoring. A working backward strategy is adopted for the monitoring process.

Collaboratively, the student demonstrates a marked shift from an almost passive member in the entry dyad. Entry data shows low positive interdependence with no assumption of roles, low participation for joint co-construction of JPS, little collaborative turn taking and low participation. In the exit CGPS, the student participates in the joint initial exploration of the problem, in planning and in the execution of agreed strategies. Mik assumes a critic’s role by monitoring the written stages of the solution, checking algebraic manipulations and engaging in argumentation with other group members. There is specific turn taking during the problem-solving process. The student participates in establishing the joint problem space without being prompted and in repairing shared meaning by explaining resonance. Mik assumes various roles within the established joint problem space. He proposes and critically evaluates group member inputs with respect to the problem state. In contributing to the group processing, Mik monitors the solution path (table 4.30) and proposes changes.

12:00	Jamal calculates “ ... 0.6 ... ” Nik “ ... Mik, check if the answer is reasonable ... ”
12:30	**Mik checks working and nods.** Mik “ ... ok next question ... ”

Table 4.30: Individual accountability during exit CGPS by Mik.

Mik demonstrates a high self-efficacy by giving a high confidence rating on most problems (03:00 -04:30). He explains the kinetic energy in collisions (08:30), checks group solution (12:30) and clarifies the simple harmonic motion problem (15:30).

4.5.3 Findings for Sue

A: Entry

The entry data showed evidence of possession of a basic problem-solving strategy heuristic (*data → equations → substitution → solution).* For routine problems requiring calculation, there is explicit extraction of data for quantitative problems. Evidence from the entry data points to the following reasons as the cause for low attainment:

1. Inadequate exploration of causal relations in solving qualitative analytical problems.
2. Incorrect interpretation of problem conditions, e.g. incorrect use of relations in the form of equations or any analysis not based on clear physics concepts.
3. No clear planning that deploys diagrams to model scenarios; where diagrams have been used, there is an incorrect analysis.
4. A clear lack of strategies on solving analytical problems, resulting in loss of marks.
5. The solution is not linked to the problem context.

Metacognitive processing is at a basic level. Planning and execution are simultaneous for routine problems, suggesting the existence of a schema. Monitoring is limited to checking progress of work with little evaluation of solutions and progress. This entry data show a good, heuristic-based approach to routine quantitative problems. For these problems, the problem-solving process is characterised by a quick retrieval of equations and almost automated algebraic manipulations of mathematical relationships for the chosen equations. The student spends little time establishing problem demands, further evidence for the existence of schemata for routine problems.

However, the student fails to proceed beyond routine problems, giving up on context-rich problems and qualitative analytical problems. There is no attempt at modelling the context using existing physics knowledge. The student does not attempt the qualitative analytical problems. Another factor is lack of appropriate physics knowledge. An example of a verbalisation that indicates inadequate knowledge structures during the entry CGPS is: ... *there is something called de-excites ...*?. However, section 2.5.4 of the OCR-GCE A physics specification requires the students to "... describe the origin of emission and absorption line spectra ..." (GCE-Physics A OCR AS, H158 p.28).

The student shows low collaborative competence during the CGPS session. Despite efforts at promotive interaction the group makes little progress due to lack of a shared understanding of the problem and subsequent failure to establish a JPS. The student demonstrates a high individual accountability by assuming various roles, checking the group, instructing the scribe to underline key words and proposing solutions. Sue makes a noticeable effort to engage other group members and there is a significant effort to initiate the problem-solving process. However, failure to engage other group members to build a JPS results in the group attaining only 6 marks out of the 15.

Sue demonstrates a low self-efficacy as she abandons context-rich problems without attempting them. The student does not persevere with unfamiliar context-rich problems, problems that require in-depth analysis. The student quit the task. However, this failure to proceed beyond routine problems can also be attributed to absence of suitable schemata and/or problem-solving strategies.

B: End of intervention cycle 1

There is a noticeable shift in the deployment of metacognitive strategies. The initial *orientating* phase involves explicit data extraction and attention to detail with units converted to SI units. However, there is no initial exploration to assess task-specific self-efficacy. This possibly leads to a trial-and-error approach and poor progression for the difficult problems.

There is clear planning on problems with well-developed schemata. For clearly planned problems, execution follows planning but then the student resorts to a trial-and-error approach due to lack of problem comprehension. The student adopts a working forward strategy for some problems with well-developed schemata. The student reads the problem statement slowly again, monitoring her comprehension and then changes her problem-solving path. However, there is inadequate monitoring of problem comprehension. The student fails to realise that $u = 0\ ms^{-1}$ for the ball (12:00) and hence uses the wrong equation. The excerpt (table 4.31) illustrates the shift to an in-depth initial exploration (09:00 -10:30) and the impact of monitoring (12:00-16:30).

09:00	Moves to part c, reads the question and underlines the data "... 38 ms^{-1} ... and the ball is stationary ..." Extracts implicit data as u= o m/s. Reads question slowly again.
	"… so the mass of the tennis ball is ... m_T= 0.058 kg … " Extracts data and converts 4.2 ms to seconds.
10:30	Writes $F.\Delta t = \Delta P_{ball}$, makes F subject of the formula.
	Good logical progression with minimum effort suggesting existence of schema.
11:00	Substitutes the values and writes the answer.
11:30	**Failure to interpret equation from insufficient question comprehension results in error in substitution. The force on the ball should involve Δp of the ball ($u = 0\ ms^{-1}$). Monitoring should have resulted in identifying the error**.
12:00	
12:30	Moves to part (iii) of the question and reads " *… estimate the mass of the racket …* "
13:00	Scans and re-reads the question again slowly.
13:30	Writes down F = 82.9 N.
14:00	Scans again and erases 82.9 N.
14:30	Taps the calculator. .. **Monitoring results in change in strategy.**
15:00	Changes approach ... writes law of conservation of momentum.
15:30	Substitutes values.
16:30	Writes M_R =0.503 kg, checks answer and moves to next question.

Table 4.31: An in-depth exploration of a quantitative problem by Sue

Despite the failure to note some implicit data from the problem statement, the student extracts the data and outlines the fundamental concepts in the form of equations. There is a good selection of physics concepts for familiar problems (0:00 to 04:30), applying specific concepts to the specific conditions of the problem, leading to a rapid progression as the student adopts a working-forward approach. There is a clear and timely substitution of variables, including conversion of units, demonstrating a good grasp of the necessary mathematical procedures in most cases. Consistent progress from problem statement to solution is limited to familiar quantitative problems.

The student lacks a coherent approach to qualitative analytical problems with a failure to move to other solution paths once stuck, lapsing back to unsuccessful trial-and-error approaches. Data from the G482 script indicate a lack of in-depth knowledge on some topics, e.g. particle oscillations in waves. This seems to result in the retrieval of incorrect equations, leading to incorrect application of physics laws. This suggests inadequate comprehension because the student lacks sufficient schemata for these types of problems. For qualitative analytical problems, there is no clear planning that involves modelling or exploration of causal links. However, data from the G482 script data indicate that there is an increase in attainment for the qualitative analytical problems. Although a trial-and-error approach is adopted with limited success, the student demonstrates higher self-efficacy. Despite noting the increase in difficulty in the other problems on momentum, the student persists with the problem. This marks a shift from the entry data where the student would have abandoned the problem.

Succinctly, a more in-depth initial exploration of the problem state, good logical progression with timely deployment of metacognitive strategies and an increase in attainment in the G482 external examination demonstrate an increase in self-efficacy (figure 4.13). However, this attainment can be attributed to a better comprehension of the problem demands, leading to an increase in attainment of the basic recall problems (QL-B) and qualitative analytical problems (QL-AN).

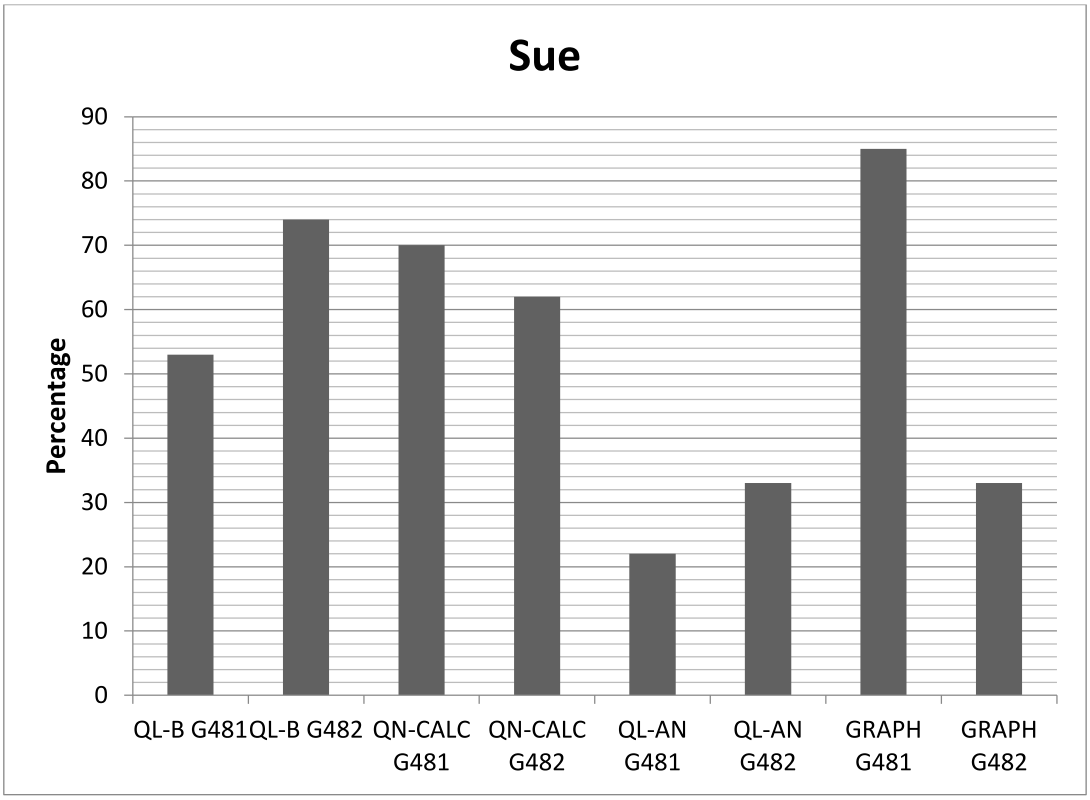


Figure 4.13: Comparison of G481 and G482 by problem type - Sue.

Despite showing an improvement in the QL-AN problems in the G482 exam script, video data show a lack of rigour in planning the solution. The improvement shown in the G482 attainment in QL-AN can be attributed to extensive writing with causal explorations but no prior planning to warrant full marks. There is still absence of clear planning that involves modelling or exploration of causal links to solve qualitative analytical problems. In some cases, there is inconsistent logical progression with no clear data extraction or planning for quantitative analytical problems.

C. End of cycle 2

Video data reveal a further shift in metacognitive processing. The *orientating* phase is marked by an initial assessment of the student's self-efficacy, rating her knowledge relative to the problems. In addition, as evidence of a more focussed exploration to increase problem comprehension, she underlines key words from the problem. This purposeful exploration is followed by explicit data extraction.

The *planning* phase is shorter compared to the orientating and execution phases. The student monitors all the orientating, planning and execution phases. There are repeated pauses and slow re-reading of the problem statement (09:00, 13:00 and 20:30). Monitoring at 11:00 results in a change in confidence rating to 30 and moving onto problems with higher confidence ratings. There is also monitoring of the execution procedure (06:00 and 07:30). There is evidence that the student evaluates her progress and knowledge resulting in moving to problems of higher confidence rating, changing the initial confidence levels and evaluation of physics knowledge in relation to the context. However, modelling is not used where it could be useful for qualitative analytical questions, e.g. explaining Newton's Third Law and analysing projectile motion. There is no planning for qualitative analytical question and poor execution, resulting in a low score.

Data from CGPS video concur with the individual problem-solving data. As part of the orientating phase, Sue insists on the scribe underlining key facts (table 4.32). Sue monitors her understanding and group progress during the planning phase.

03:00	"...That's easy ...it´s easy ... (reads on)...not actually ... "
08:00	" ... no ... no , you have to underline ... "
14:30	Jamal. "... omega by X ... " Sue. "... are you sure? ... There is a square somewhere omega squared..there is amplitude ... "

Table 4.32: Monitoring of group understanding during CGPs –Sue.

By engaging Jamal in monitoring the shared understanding, the group repairs the initial equation proposed by Jamal. In addition, Jamal is considered the most able and usually his contributions go unchallenged. Sue demonstrates a high self-efficacy in challenging and correcting his contribution. However, the evaluation of solutions is still inadequate. As an example, writing the final answer for the velocity of the plane as 5.48 x 10^5 m/s shows lack of evaluation of answers (table 4.33).

14:00	Writes down equation *"... F is equal to mv^2 over r ... "* Makes "v" subject of the formula
	Substitution of values and calculates v *"... 5.48 x 10^5 m/s ... "*

Table 4.33: Inadequate evaluation of solution – Sue

An evaluation of the cognitive competences shows an adoption of a working forward strategy with an in-depth analysis of the problem as illustrated by her deriving equations from first principles to verify key equations. The excerpt from the protocol of the exit video (table 4.34) illustrates this shift. At 17:30, the student conducts a rough working to verify equations and then moves back to solving the problem. This also illustrates high self-efficacy. In addition, the student’s evaluation of successfully solving the problem as part of initial exploration averages 70%.

15:30	*“... Ok ... v equals 2* π *times r ... mmmm ... F= m x V ... ”* **Sceptical about answer adopts a trial and error approach.**
	Writes and erases.
16:00	*“ ...* $g = -GM/r^2$ *and* $F = GMm/r^2$ *... “* writes on the side... to trial the retrieved equation. **Retrieval failure.**
16:30	*“... v equals ... ah I forgot ... ”* pauses *“ ...* $V^2 = 4$ *´pi´ squared* r^2 *over* T^2 *...”*
17:00	*“ ... v squared is equal to GM ... ”* Erases and pauses.
	Student proceeds through trial and error rather than an initial qualitative approach.
17:30	Conducts rough working at the bottom of the page.
18:00	Derives the equation for V^2 from the basic concepts.

Table 4.34: Deriving key equations from basic principles -Sue

Data from the CGPS videos further demonstrate this clarity of concepts and its timely deployment in the initial qualitative exploration of the problem (see 01:00 of the verbalisations during the CGPS in table 4.33). Sue demonstrates clarity of physics concepts. In one of her contributions, she highlights the importance of a reference system when working with vectors (08:30 in table 4.35). There is a clear contribution on the specific physics relationships and the mathematical procedures involved. As evidence of an increased self-efficacy, Sue engages in collaborative argumentation with Jamal and also critically analyses other group members’ contributions (table 4.35). The student engages in *joint co-construction of knowledge, establishing* a shared meaning of the problem as part of the initial exploration of the whole task (11:00 in table 4.35).

01:00	Sue *“... kinetic energy is not conserved ... the second ... is not ... become in inelastic collisions KE is conserved...”*
08:30	*Sue “... I think you have to have that reference point ...we have to write down which one is positive ... so we take that one a positive ... ”*
09:00	Jamal*. “... Can we just do ½* mv^2 *minus ½* mu^2 *...?”*
11:00	Sue *“ ... F delta P over delta ... ”* Jamal*.”... so the change in momentum is.... ”* Sue. *“... is mv minus mu ... ”*
12:00	Sue *(*writes **mv** minus and minus **mu)** “**...** *yeah .. yeah ... ”*
	Sue. “... huh...you still have to put a reference point...oh yeah ... ”
14:30 :	Jamal. *“ ... omega by X ... ”* Sue “*... are you sure? ...There is a square somewhere... Omega squared ... there is amplitude ... ”* Mik *“ ... amplitude is displacement ... ”*

Table 4.35: A shift in collaborative competences by Sue

The student consistently contributes to the problem-solving process, assuming various roles, from proposing solutions to criticising contributions and checking written solutions. The student participates in the construction of the JPS (confidence ratings of problems), maintaining shared understanding through the problem-solving process and exploring the merits of contributions by other group members. The student also undertakes to check written solutions.

While the exit data point to a limited shift in solving qualitative analytical problems, there is sufficient evidence to indicate a positive shift in the student´s self-efficacy, metacognitive processing and collaborative competences. These shifts explain the noted positive shift in problem-solving competences.

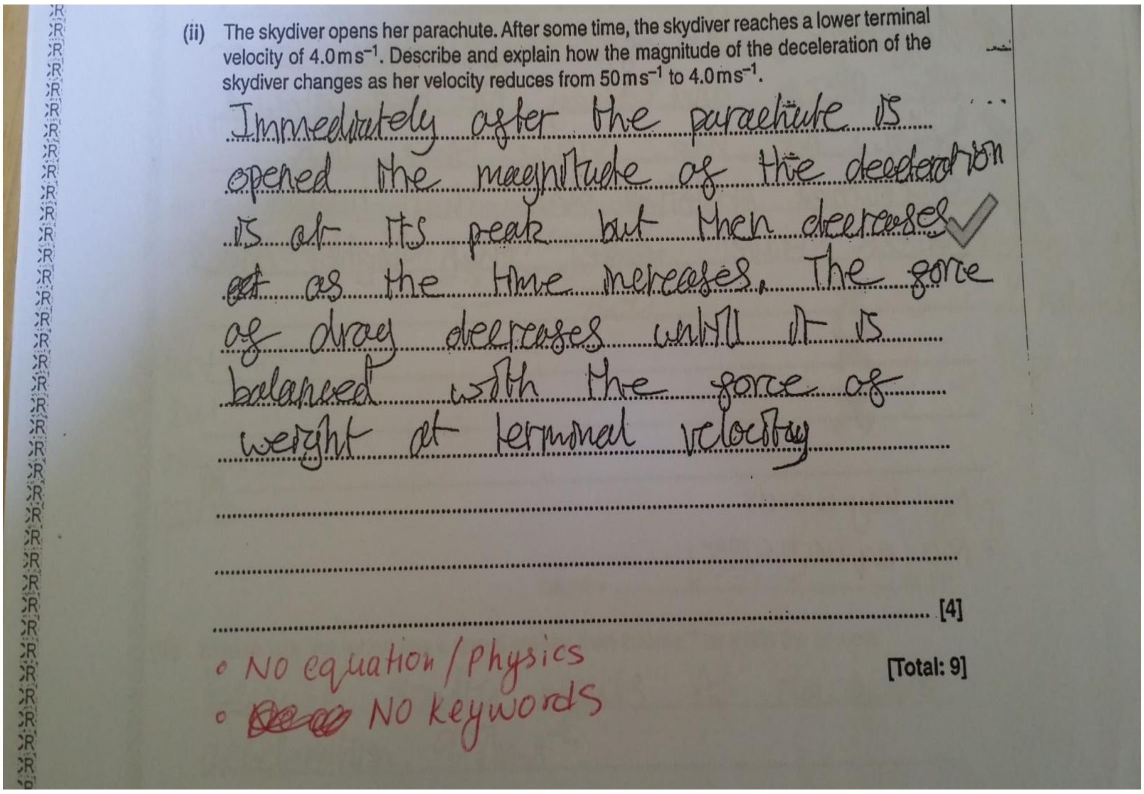
4.5.4 Findings for Nik

A. Entry

Evidence from Nik’s G481 examination script revealed major flaws in conceptual knowledge and a lack of problem-solving strategies. The student lacked a coherent body of the required scientific knowledge and relevant problem-solving skills in the form of appropriate schemata related to the set task. As an example, during the CGPS, the student proposes and draws an incorrect diagram on stationary waves. There is an attempt to guess possible solution paths. In some cases, the student deploys a basic heuristic approach to problem solving (*data* → *equations* → *substitution* → *solution*). However, this working forward approach does not extend beyond quantitative problems or problems that require the use of one or two physics relations in the form of equations. The lack of in-depth analysis of the context as part of the initial exploration of the problem leads to incorrect retrieval of equations. This suggests the lack of a robust problem-solving schema. There are inaccurate mathematical procedures, leading to inaccurate solutions. Some problems were not attempted, reflecting low self-efficacy. Inadequate physics knowledge hinders success in monitoring progress:

> *08:00: Nik "... lets re-read the question ... it must be constructive then ..."*

The G481 script buttresses the evidence of a lack of appropriate strategies in solving qualitative analytical problems. An attempt at solving the problem results in the solution reduced to extended writing without the use of models and relevant physics concepts, in the form of equations, to buttress the argument (figure 4.14).



(ii) The skydiver opens her parachute. After some time, the skydiver reaches a lower terminal velocity of 4.0 m s^{-1}. Describe and explain how the magnitude of the deceleration of the skydiver changes as her velocity reduces from 50 m s^{-1} to 4.0 m s^{-1}.

Immediately after the parachute is opened the magnitude of the deceleration is at its peak but then decreases ✓ ~~at~~ as the time increases. The force of drag decreases until it is balanced with the force of weight at terminal velocity

[4]

- No equation / Physics
- No keywords

[Total: 9]

Figure 4.14: Inadequate approach to qualitative analytical problems- Nik

There is very little evidence of the deployment of metacognitive strategies during the problem-solving process. Attempted efforts at monitoring or evaluation, on the basis of inadequate scientific knowledge, yield no positive outcomes. Further evidence of a lack of metacognitive monitoring is from the CGPS video data when the group engages in a random and unplanned fruitless pursuit of the solution for 12 minutes, eventually abandoning the task.

Low collaborative competence is reflected by frequent social loafing by Nik during CGPS. *Social loafing* occurs when individual´s group participation is lacking or non-existent due t*o either poor motivation or other* circumstances. The tendency is to reduce individual effort when working in groups compared to the individual effort expended when working alone (Williams & Karau, 1991).This social loafing can be attributed to low self-efficacy and poor collaboration. In addition to wandering off during the task, there is little effort by the student to establish team organisation. There is low *positive interdependence* by the student as part of the group. Group effort scores 6 marks out of the possible 15 marks. There is an attempt to contribute to the formulation of the solution but, with little contribution from other group members, the action and communication do not advance the solution process. Low i*ndividual accountability* and inadequate *promotive interaction* which contribute to the low *group processing* confirm the data on low attainment.

B. End of cycle 1

An analysis of the G482 examination script reveals an overall improvement in attainment. Despite being perceived as the harder of the two modules, the student scored 57% as compared to 43% for G481. However, this might be also be attributed to the student maturing. In response to this objection, the solution steps in the answer scripts reveal evidence of taught strategies. The student shows a clear initial exploration of the problem, underlining key words. This can also be interpreted as evidence of comprehension monitoring. Initial planning involves writing equations before stating definitions and also exploring causal links. There is a clear logical progression towards the solution in most cases.

There is still evidence of inadequate comprehension or existence of schemata which may be the cause of the observed low attainment in qualitative analytical problems. Still, a comparison of the performance, G481 vs. G482, by problem type shows a marked improvement in solving qualitative analytical problems (figure 4.15).

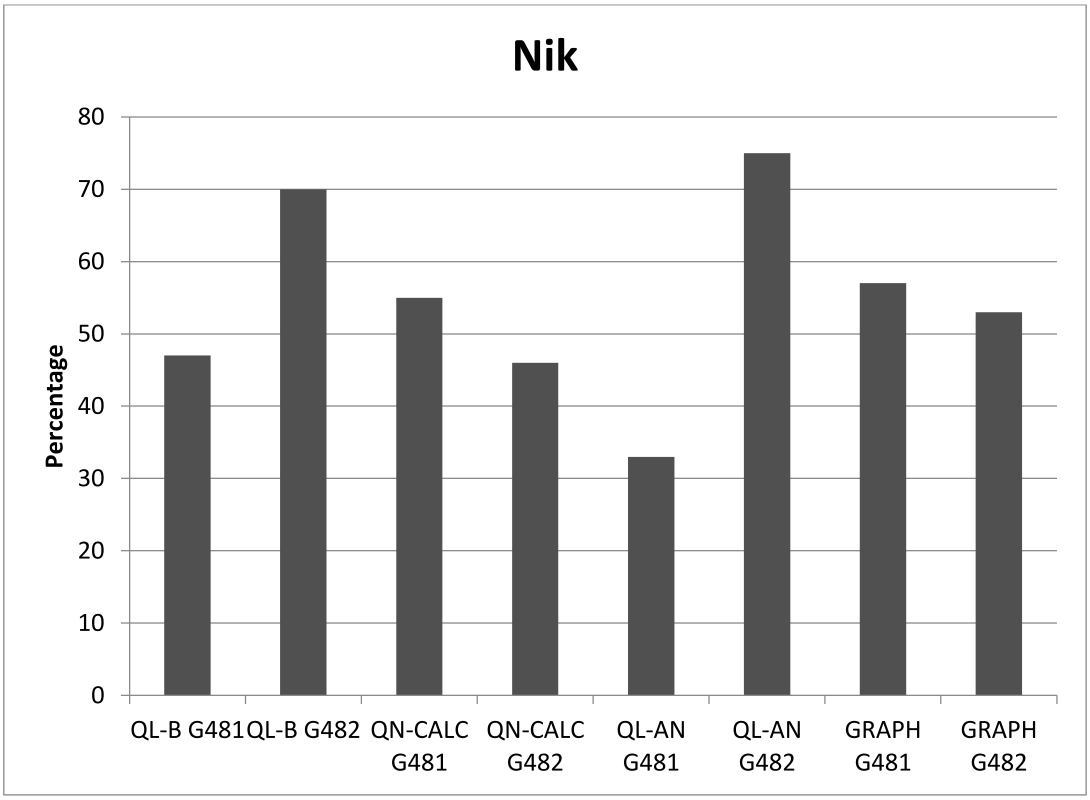


Figure 4.15: Comparison of G481 and G482 for Nik.

Despite the noted shift, the student fails to model or produce a visual representation of most problems to aid comprehension. Unsolved quantitative calculation problems indicate possible absence of schemata for these types of problems.

Video data to probe for metacognitive processes indicate a positive shift as the student notes the problem demands and undertakes a purposeful exploration of the problem. The student uses metacognitive self-prompts with a step-by-step noting of problem conditions (table 4.36). This orientating process is illustrated in the excerpt from the student´s protocol. Planning follows orientating with explicit extraction of the given data, including adding a reference frame and modelling of the scenario after impact. Specific equations reflecting the context are also noted with a timely execution of the plan, showing a working forward strategy. Rapid progress during the process indicates the existence of schemata in this domain of mechanics.

02:30	Reads next question “*... fig. 2 shows the masses and velocities ...*” Underlines key

	phrases directly towards each other, stick together and common velocity.
03:00	*“ ... so I have underlined the key terms ...* **”**
	“... the diagram is already given ... so I will leave it out … but it does not have a reference frame ...” Draws a reference frame. **Good planning and metacognitive self-questioning.**
03:30	Pauses and studies the diagram “*... so this is before impact ... ”*
	“ ... *After impact* …” writes down and pauses “... *A and B ...* **”** draws two interacting objects and a reference line ... ” “ ... *they have different masses …my point of reference …”*
	Good use of strategy, modelling of scenario after collision.
04:00	Draws an arrow on the reference frame, pauses “... *mmmm* ...” erases arrow and draws it in the other direction.
04:30	*“... so mmm. The key phenomenon here ... conservation of momentum ... ”* **Good scientific knowledge**.

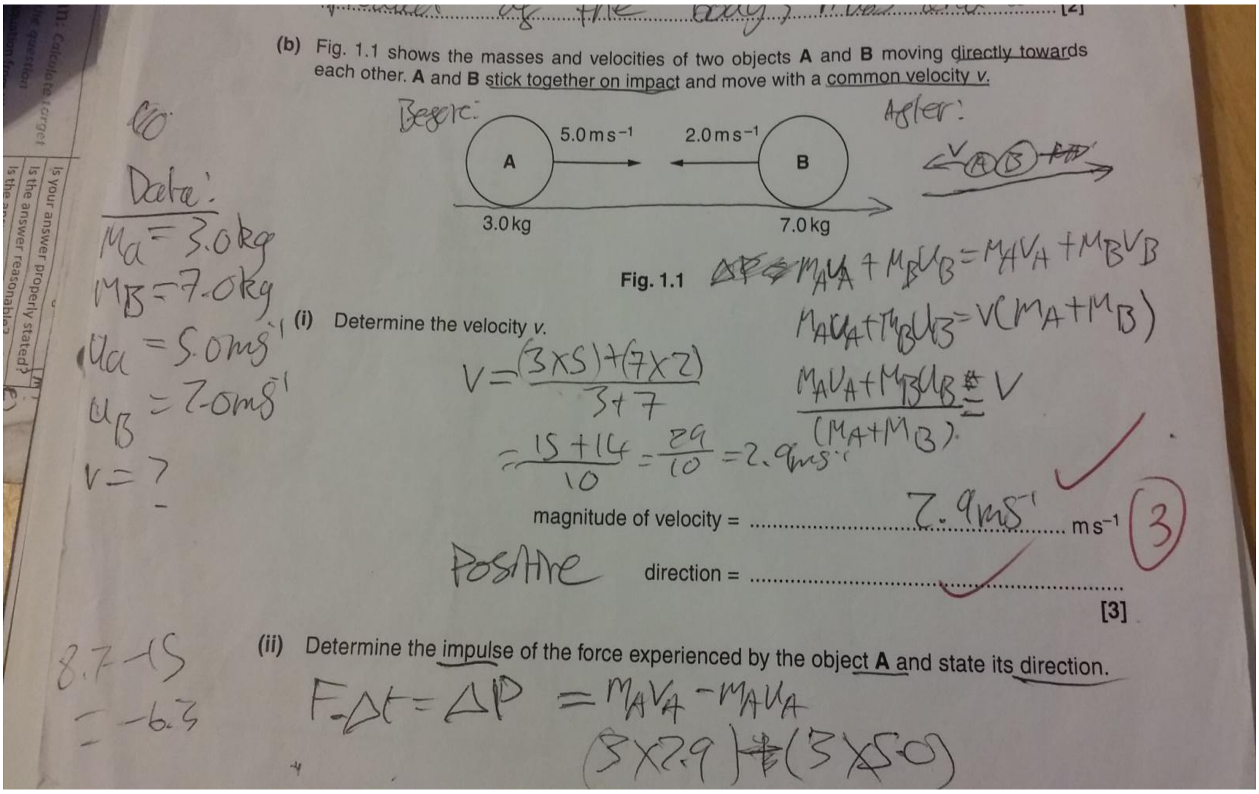
Table 4.36: Orientating during initial exploration of the problem state -Nik

The verbalisation “... *so I have underlined the key terms ...***”** at 03:00 indicate metacognitive self-prompts from learnt strategies. There is evidence of regular monitoring of comprehension (03:00, 03:30 and 04:00). There is also monitoring of the use of a heuristic (06:30). When the student monitors his comprehension (09:30) he decides to skip the question (table 4.37).

09:30	Reads next question. Deep sigh … **realises the complexity of the question**
	“ ... I will come back to this one ...”

Table 4.37: Comprehension monitoring resulting in change in approach

There is a noticeable shift in the *useful description* and *physics approach* though these competences are hard to distinguish at a practical level. There is an initial exploration of the problem by reading and underlining key terms and then proceeding to extract the data. There is modelling of the scenario and highlighting the domain concepts. This indicates a deeper approach to problem-solving. Key physics concepts are then selected with a clear illustration of the scenario and correct specific application of physics as the student establishes a clear connection between the model, the selected equations and the data with the law of conservation of momentum clearly employed (figure 4.16).



(b) Fig. 1.1 shows the masses and velocities of two objects **A** and **B** moving directly towards each other. **A** and **B** stick together on impact and move with a common velocity *v*.

Fig. 1.1

Data:
$M_a = 3.0kg$
$M_B = 7.0kg$
$u_a = 5.0ms^{-1}$
$u_B = 2.0ms^{-1}$
$v = ?$

$M_A u_A + M_B u_B = M_A v_A + M_B v_B$
$M_A u_A + M_B u_B = v(M_A + M_B)$
$\frac{M_A u_A + M_B u_B}{(M_A + M_B)} = V$

(i) Determine the velocity *v*.

$V = \frac{(3\times5)+(7\times2)}{3+7}$
$= \frac{15+14}{10} = \frac{29}{10} = 2.9ms^{-1}$

magnitude of velocity = 2.9ms⁻¹ m s⁻¹ ③

Positive direction =

[3]

(ii) Determine the impulse of the force experienced by the object **A** and state its direction.

$8.7 - 15$
$= -6.3$

$F\Delta t = \Delta P = M_A V_A - M_A U_A$
$(3\times2.9) - (3\times5.0)$

Figure 4.16: Working forward with clear specific application of physics

The student perseveres with difficult problems and demonstrates a systematic and methodical progression through the problems by deploying heuristics. The verbalisations reflect metacognitive processing and sound physics knowledge relevant to the task. The student confidently progresses through the problem-solving process showing a higher level of self-efficacy than in the entry data.

C. End of Cycle 2: Exit

In addition to the shift noted at the end of cycle 1, the student assesses his current state of knowledge relative to the problem-solving task, assessing self-efficacy using confidence ratings. Problem solving begins with problems with the highest rating. The student mostly adopts a working forward strategy on problems with well-developed schemata. Execution of a planned solution path is abandoned when Nik is confronted with an unfamiliar problem. In the exit video, the student embarks on a trial-and-error approach for six minutes. While this can be interpreted as little monitoring of progress and time, it also indicates a high self-efficacy; the student did not just abandon the problem!

There is evidence of little evaluation as noted by the rather obvious conceptual error $V_A = M_A$. There is no evaluation as to the significance of this relationship. However, the observed reduced evaluation of correct solutions might also reflect high confidence of the student, especially if the problems have been successfully solved.

CGPS exit data shows the persistence of incomplete knowledge structures in some physics domains and inadequate comprehension of the problem demands. The excerpt below (table 4.38) illustrates this observation.

05:00	Jamal. “ ... use of resonance ...?”
	Nik. “... i think it’s when we have to ... ”(*inaudible)*
	Jamal. “ ... but that’s not useful ... ”
	Nik. “... but I thought resonance ... there has to be the same frequency ...”

Table 4.38: Inadequate scientific knowledge -Nik

However, as the scribe during the CGPS, Nik shows clarity of understanding of the concepts required to solve the problem. He re-arranges suggested equations, substituting the data and producing solutions consistent with the agreed approach. His contribution to the joint problem space and subsequent ‘distilling’ of the group discussions indicates a much deeper understanding of the physics concepts compared to the entry video data. In contrast to the entry data on collaboration, Nik participates in establishing team organisation and formulation of strategy through assuming a role as a scribe and a proposer, a major shift in collaborative competences. The student engages in co-construction of the solution path. The extract (table 4.39) illustrates where the students participate in specific turn-taking.

06:00	**N**. *“ ... I think we can say we have 50% here ... we can get half the question ... ”* **S**. *“... we start solving the problems ... the first one has the highest rating ... ”* **S**. *“... question Part B ... ”* N. “... *no we have got another one with 100%* ... (flips through***)*** “ *...yeah 100*

	right here ... "
07:00	**S**. "... *why didn't we do b*? ... " **N**. "... *because this one has the highest confidence rating* ... "
11:00	N. "... *so magnitude of the average force*... ". S. "... *F delta P over delta t*?... " J. "... *so the change in momentum is* ...." S. "... *is mv minus mu* ... " N. " ... *so change in speed is 21* ... "

Table 4.39: specific turn-taking during CGPS-Nik

Exit data point to a high level of individual accountability with no incidents of social loafing as the student engages with the group, assuming the main role of scribe throughout the task. The student partakes in establishing and maintaining a joint problem space, planning on how to start the task and partakes in discussing time - management strategies with group members. Undertaking the role of scribe and writing down agreed solution steps with minimum supervision from other members indicates increased confidence. In addition, Nik remains engaged with the task as the group discusses how to solve the problem, with various repairs taking place and re-establishing task demands.

CHAPTER 5.0: DISCUSSION AND CONCLUSIONS

The purpose of this study was to examine the impact on the problem-solving process of explicitly teaching physics problem-solving strategies to a group of GCE-A level students in an inner London academy. The results were not as homogenous as most literature would suggest. This chapter will discuss these results as well as the limitations and implications for practice.

5.1 Overview of the study

The impact of the explicit teaching of problem-solving strategies in physics is well documented in education and cognitive research literature, with seminal work by Schoenfeld (1992) on mathematics and the Minnesota physics problem-solving model (Heller & Hollabaugh, 1992). Other studies that have contributed to the literature on the explicit teaching of problem-solving strategies in physics include those of Larkin (1983), Chi, Feltovich and Glaser (1981), Reif and Heller (1982), Van Heuvelen (1991) and Heller, Keith and Anderson (1992). In the UK, few studies on physics problem solving have been documented. Searches yielded work by Bolton and Ross (1997) and Abdullah (2009). Studies on explicit strategy instruction in physics have had a quantitative focus with quasi-experimental designs and no focus on the mechanisms that are supposed to be triggered by the intervention strategies (Heller & Anderson, 1992; Huffman, 1998; Chi & Vanlehn, 2007; Selcuk et al., 2008).

This study sought to explore this gap in knowledge, examining the possible mechanisms triggered by the explicit teaching of strategies within a collaborative context. An action research methodology consisting of two intervention cycles was adopted, steeped in three theoretical frameworks: socio-cultural theory, socio-cognitive theory and information processing theories. The study sought answers to the following research questions:

1. How do A-level physics students in an inner London comprehensive school approach GCE-A level physics problem solving?
2. What generative mechanisms are triggered to bring about a change in the approach to physics problem solving (PPS) by the explicit teaching of strategies and how do these generative mechanisms compare to the existing approach?

5.2 The first research question

RQ1: How do A-level physics students in an inner London comprehensive school approach physics problem solving?

To address this first research question, an analysis of the January (OCR-A G481, 2014) external exam scripts and entry videos on problem-solving (individual and collaborative) was undertaken. As discussed in chapter 2, successful physics problem solving hinges on possession of general and powerful strategies like means-ends analysis and sub-goaling (Simon & Newell, 1972; Greeno, 1976; Larkin, 1980). Problem solving as a conscious cognitive activity, requiring one to control one's own thinking, is subordinate to executive decisions as the student determines what solution path to follow or not follow, when to change this solution path, and how resources like time must be allocated (Flavell, 1977; Schoenfeld, 1985; Armour-Thomas et al., 1992). However, Schoenfeld (1985) argues that competence in problem solving hinges not only on effective deployment of cognitive and metacognitive strategies but on stable conceptual models. This study, though conscious of the role of these conceptual models, did not explore the impact of conceptual models on problem solving but referred to them in some instances.

The possession of good cognitive and metacognitive problem-solving strategies can be overruled by self-doubts; hence, effective functioning requires both skills and efficacy beliefs to use them well. Self-efficacy, a key factor in the generative system of human competence, allows for the effective organisation and orchestration of the cognitive, social, emotional and behavioural domains (Bandura, 1997). Students who regard themselves as efficacious will persist longer on difficult problems than those with lower self-efficacy, who may choose to avoid the task (Collins, 1982; Hoffman & Schraw, 2009). This was evidenced with two students from this study (Jamal and Mik); whom despite lack of strategies and solid conceptual knowledge they persisted with the problems. Studies in mathematics have shown that self-efficacy is also a stronger predictor of math performance than either math anxiety or previous math experience and influences math performance as strongly as overall mental ability (Pajares & Kranzler, 1995; Pajares & Miller, 1995). Self-efficacy has a powerful influence on an individual's motivation, achievement and self-regulation (Bandura, 1997;

Schunk & Pajares, 2009). Self-efficacy develops during and also influences social interactions.

The theoretical argument for this study is that; the development of the internal mechanisms – cognitive, metacognitive and self-efficacy – is anchored in social interactions. Vygotsky (1978) noted that a child's cultural development appears first on the social level and then on the personal level, whereby higher functions originate as actual relations between human individuals. This view buttresses my argument in this study, that the development of internal dialogues in problem solving is a product of interactions during collaborative group problem-solving sessions through cognitive apprenticeships. A deficiency in the internal mechanisms at an individual level is a symptom of inadequate pedagogic approaches with little emphasis on developing collaborative competences.

All cognitive and metacognitive functions originate on the social level and are then internalised at the individual level. This highlights the role of collaboration in designing interventions aimed at improving physics problem solving. The initial analysis focussed on the extent of cognitive and metacognitive processing during problem solving, student self-efficacy and the level of collaborative competences.

The entry data revealed the deployment of a general heuristic approach for quantitative calculation problems (QN-CALC) (*data → equations → substitution → solution*). With this approach, students read the problem and extract the data, noting the givens and the target quantity. Explicitly writing down the data and problem conditions reduces cognitive load on the working memory and allows for the evaluation of the solution (Sweller, 1988). With this approach, success is limited to those problems where students simply look for plausible equations with little or no regard to applicability of concepts. Only two of the students showed consistence with this strategy.

Context-rich problems are not a common feature in GCE-A level physics (Heller, Keith, and Anderson, 1992; Heller and Hollabaugh, 1992). However, they share a common feature with qualitative analytical (QL-AN) problems. Both types of problems allow a deeper exploration of the problem by presenting the problem as a real life scenario and are also closed. This means that there exists a single solution and that there are only a small number of valid solution paths for the problem. However, the GCE-A level QL-AN problems form part of a scaffolded problem, usually with a model provided. In both types of problems, the students showed a clear lack of strategy, relying on extensive writing without any initial planning or exploration of causal links. There is limited external representation of problems from an oral or written form to a visual form in the form of diagrams, models, sketches or graphs and then to a mathematical form. Key to success in solving context-rich and QL-AN problems is representation or modelling. Representations are the hallmark of an expert-like ‘approach’ to physics problem solving (Chi et al., 1988; Kohl & Finkelstein, 2008; Etkina et al., 2009). The transformation of the problem to a visual form serves as a window to students’ cognitive processing. Where students attempted a representation, there was a failure to link the representation to the appropriate physics concepts. Hestenes (1987) argues that the modelling strategy is viewed as a general problem-solving strategy that must be taught explicitly to physics students.

All four students spent most of their allocated time on the initial exploration stage, with constant re-reading of the problem statement, indicating the absence of a well-developed and practised schema. The existence of ‘problem schemata’ is evidenced by students’ ability to categorise problems quickly (Hinsley et al., 1978; Chi et al., 1981). A rapid establishment of correspondence between externally presented events and internal models reflects an expert approach (Chi et al., 1981).

Metacognitive processing during problem solving, though it is hard to distinguish between cognitive and metacognitive activities at a practical level (Artz & Armour-Thomas, 1992), were probed by analysing the verbalisations and actions from the thinking-aloud protocols (Meijer et al., 2005). The data show inadequate orientation leading to poor or no planning with little monitoring of progress or evaluation of solutions and solution paths. Inadequate metacognitive processing limits success rate in problem solving argue Theide et al (2003). In addition, the entry data show that the four students had limited metacognitive processing during problem solving, leading to their success being limited to those problems the students already possess established schemata. Success in problem solving largely depends on case reuse-schemata retrieval and transfer- when students extrapolate information collected and stored from previous problem-solving experiences to determine how it might be comparable to the new problem (Jonassen, 2006).

The intrapsychological processes involved in the social interactions during collaborative group problem sessions are considered to pass to the intrapsychological plane through appropriation (Rogoff, 1991; Dillenbourg et al., 1996). Collaboration is an external mechanism that must be triggered for the development of cognitive and metacognitive skills and self-efficacy, and their subsequent triggering during the transfer process. Entry data revealed low levels of collaboration when working in CGPS. Learning is a social activity and successful collaboration will sustain the students' motivation. Successful collaboration involves a large degree of mutual engagement, joint decision making and discussions (Roschelle & Teasley, 1995). In one of the CGPS groups, members failed to engage with the set tasks and build a joint problem space with frequent incidents of social loafing. Due to a low promotive interaction, attempts to move the problem forward proved futile. The lack of an initial shared understanding resulted in no positive interdependence as individual students attempted to solve the problems on their own, reducing the process to a group activity instead of a collaborative one. Low group processing across all the groups was reflected through individual random efforts and trial-and-error approaches. In one case, Jamal and Mik, there was a lack of performance optimisation as Jamal assumed the roles of scribe and manager, independently solving all the problems.

The advantage of collaboration is that the output of the group in solving the problem can be greater than the sum of the outputs from individual members (Aronson & Patnoe, 1997; Dillenbourg, 1999; Schwartz, 1995; OECD, 2013). In addition to that benefit, this study also viewed collaboration as an external generative mechanism that must be triggered to develop cognitive and metacognitive skills, and self-efficacy to foster competence in problem solving.

The possession of good cognitive and metacognitive problem-solving strategies can be overruled by self-doubts; hence, effective functioning at an individual or group level requires both skills and efficacy beliefs to deploy these strategies well. Self-efficacy has a powerful influence on individuals' motivation, achievement and self-regulation (Bandura, 1997; Schunk & Pajares, 2009). Not be confused with academic self-concept which refers to individuals’ knowledge and perceptions about themselves in academic achievement situations (Wigfield & Karpathian, 1991), academic self-efficacy refers to individuals’ convictions that they can successfully perform given academic tasks at designated levels (Schunk, 1991). Academic self-concept primarily indicates one’s self-perceived ability within a given academic area, while academic self-efficacy primarily indicates one’s self-perceived confidence at successfully performing a particular academic task (Bong & Skaalvik, 2003).

Some students (Sue and Nik) demonstrated a low self-efficacy leading to reduced or no attempts at solving given problems, individually or as a group. Some groups (Nik´s original group) disengaged from the tasks and some individuals (Sue) abandoned tasks that proved to go beyond the use of basic heuristics. Some students (Jamal and Mik) demonstrated a high sense of self-efficacy as they persevered with difficult problems, despite not possessing appropriate problem-solving strategies. Beliefs of personal competence also help determine how much effort people will expend on an activity, how long they will persevere when confronting obstacles, and how resilient they will prove in the face of adverse situations; the higher the sense of efficacy, the greater the effort, persistence and resilience (Pajares, 1997). Other students abandon the tasks (Nik) or solve those problems they are familiar with (Sue). Albeit the lack of familiarity with the solution, Jamal and Mik´s dyad persists with the challenging qualitative problem, progressing through various stages of trial and error and scoring seven marks out of the ten. This suggests a high self-efficacy in both students.

Succinctly, entry data showed a novice approach to problem solving with little to no metacognitive processing. Mechanisms that enable competent problem solving, i.e. self-efficacy and collaboration, ranged from inadequate to non-existent! For this GCE A level group, success was limited to problems requiring basic recall like stating definitions or recalling basic physics principles and quantitative problems where they apply a basic linear heuristic approach (read → extract data → equations → substitution → solution).

This low attainment can be attributed to a lack of strategies to solve problems that demand an in-depth analysis of the problem and well-developed conceptual knowledge, i.e. context-rich problems and qualitative analytical problems. This novice approach correlates with the low collaborative competences observed in CGPS sessions and inadequate metacognitive processing revealed in the entry data. Within the context of physics problem solving, this includes poor time management, inability to map a clear direction of the solution path or to determine the next solution step, lack of monitoring of understanding or progress and failure to ask oneself sceptical questions as a guide to progress (Heller, 2009).

These findings were discussed with the students and formed the basis of the intervention strategies. The intervention process also involved the teaching of explicit strategies to solve all types of problems within the GCE-A level physics course. The Minnesota problem-solving model was adopted for the first cycle. The intervention period spanned almost the same length of period (March 2013 – October 2103) as that of traditional teaching (September 2012 – February 2013).

5.3 The second research question

Data collected from the G482 scripts and individual and CGPS video data were analysed to answer research question 2.

***RQ2**:* What generative mechanisms are triggered to bring about a change in the approach to physics problem solving (PPS) by the explicit teaching of strategies and how do these generative mechanisms counteract the existing approach?

The two interventions cycles for this action research study were grounded within socio-cognitive, information processing and socio-cultural frameworks. The aim was to trigger the generative mechanisms of self-efficacy and collaboration, to enable the construction and subsequent triggering of the desired internal mechanisms, cognitive-metacognitive and self-efficacy, during problem solving. Periodic collaborative group problem-solving sessions were also aimed at building robust problem-solving schemata for the different domains in the modules. For logistical reasons, collaboration was not assessed at the end of the first cycle.

The entry data showed different levels of self-efficacy and cognitive attainment for the four students. Overall, for all the students, there is low metacognitive processing and collaboration. However, the exit data show noticeable shifts though different for each student. In can be argued that the prolonged explicit cognitive and metacognitive strategy instruction through collaboration, with the instruction embedded in the content matter to ensure connectivity, resulted in the development of cognitive, metacognitive, collaborative skills and self-efficacy, but differently in the individual students. Veenman, Van Hout-Wolters and Afflerbach (2006) noted that despite strategy instruction, students will develop differently. A brief recap of for each student with view to answering RQ2 is given in the following sections.

5.3.1 The highly efficacious and good mathematician with a physics target grade of B: Jamal

Jamal shifts from a trial-and-error approach to adopting a predominantly clear working forward approach, terminating in a reasonable answer. There are reduced incidents of constant reading of the problem statement and weaving between two problems. The student adopts a shortened form of the heuristic, with no explicit data extraction. However, he underlines the key facts in the problem statement. Equations are now used as part of the causal exploration to solve qualitative analytical problems. In relation to mathematical procedures, the student goes beyond basic algebraic manipulations of change of subject; he adopts a mathematical model as part of the specific approach, converting the problem statement into a system of simultaneous equations.

There is evidence of regular monitoring of problem comprehension and progress as evidence of metacognitive processing. Monitoring becomes more regular with an increase in problem difficulty. Self-efficacy remains high for this student as he perseveres with difficult problems and does little evaluation of solutions, which turn out to be correct. The student shows a marked improvement in the G482 external examination, scoring 81% compared to 53% in G481. Reviewed literature shows a strong positive correlation between success in problem solving and deployment of metacognitive strategies (Zimmerman & Martinez-Pons, 1985; Schoenfeld, 1992; Pintrich, 2000).

Exit data point to a further shift in the exploration phase with the student identifying key aspects of the problem underlining them and explicitly extracting the data. Monitoring becomes more regular and clearer as evidenced by clear verbalisations of metacognitive self-questioning prompts, e.g. "... *Is that all right ...?*" and "... *What other equation do I know for this?"* This increase in self-directed verbalisations indicates an increase in self-awareness about what the student wanted to do, using metacognitive self-prompting to guide the problem-solving process (Silver, 1982; Lester, 1985).

Failure to adopting a modelling strategy for qualitative analytical problems leads to the low attainment. Modelling or the reduction of a problem to a visual form allows for a quick perceptual check as to whether the external representation is consistent with the physical situation (Larkin & Simon, 1987. In addition, diagrams can be viewed as external representations of the mental image of the problem state, but in more detail. It can be argued that this reduces cognitive load on the working memory.

For Jamal, the clear shift to a more elaborate metacognitive and cognitive processing buttresses the argument that these mechanisms are triggered during problem solving, a consequence of explicit strategy instruction. A collaborative environment is the ´cradle` of metacognitive skills. This is where the communicative tool of language is internalised, later allowing communication with others and directing one's individual activities and cognitive processes (Vygotsky, 1967; Wertsch, 1985; Rogoff, 1990). Self-directed inner speech during problem solving, as evidenced by the verbalisations, facilitates task analysis, monitoring of progress, maintains attention (Rohrkemper, 1989). Metacognition involves focussed planning, suppressing the urge to immediately solve the given problem.

5.3.2 The highly efficacious and slow, with a physics target grade of C: Mik

Mik showed a different shift compared to Jamal. His G482 script shows a drop in marks for quantitative and graphical problems. However, the student showed a marked improvement in solving qualitative and analytical problems in the G482 exam.
As compared to the trial-and-error approach from the entry data when solving qualitative analytical problems, the student adopts a working forward approach with consistent progress from the problem statement to the specific physics equations, terminating in a reasonable answer. Diagrams are clearly linked to the specific physics.

Exit data show a thorough initial analysis of the problem state. As a time management strategy and an indication of high self-efficacy, the student rates the probability of success for each problem before attempting to solve it. With this approach, the domain of each problem is identified and the fundamental relations stated as part of this initial exploration. This can also be attributed to well-developed problem-solving schemata. It can be surmised that as a consequence of this approach, there is an improvement in time management.

Compared to the 27 minutes spent on the first cycle to solve problems worth 15 marks, the student solves problems worth 30 marks in 35 minutes. There is evidence of the existence of robust schemata and automation of mathematical procedures. In addition to a good deployment of algebraic manipulations like `change of subject´, mathematical manipulations are also used to dimensionally check the consistency of the solution). Exit data also reflect improvements in the collaborative competences.

5.3.3 From a routine problem solver to a highly efficacious collaborator: Sue

For Sue, the end of the first cycle data reveal a positive shift in self-efficacy but an inadequate approach to solving qualitative problems. The student deploys equations to help with problems requiring basic recall of definitions. In solving qualitative analytical problems, the student relies on extensive writing with limited exploration of physics principles and causal links. However, these two changes seem to contribute to the small (4%) increase in the G482 external examination despite a drop in attainment in the quantitative calculation problems. There is clear planning for problems with well-developed schemata but a trial-and-error strategy is adopted for the difficult problems.

There is evidence of increased monitoring as corrected work on script leads to correct solutions. From video data, the student monitors problem comprehension as evidenced by episodes of slow re-reading of the problem statement. An increase in self-efficacy is reflected with increased persistence and efforts to derive equations from first principles. From a metacognitive perspective, the change in the solution path and subsequent correct solution can be attributed to the increased monitoring. Shifts in metacognitive processing and self-efficacy are noted for Sue but there is no noticeable shift in strategy deployment for qualitative analytical problems.

Exit data show a shift in approach as the student adopts a novel approach, exploring the problems with a high chance of success and solving them first. There is a working forward strategy adopted for most of the problems. A high self-efficacy and good grasp of relevant physics concepts is demonstrated when the student derives equations from first principles to verify specific physics problems for the given context. The shift in attainment can be attributed to an increase in self-efficacy, increased metacognitive processing and robust problem schemata for quantitative problems. The study can argue that these were developed in the regular collaborative group problem-solving sessions. The challenge to attain full marks on qualitative problems still persisted.

5.3.4 From the near drop-out to the diligent and focussed collaborator: Nik

The new approach of the intervention strategy seemed to have produced a different student in Nik. Of the four pupils, Nik showed the biggest shift in all competences, including attainment. The first cycle showed a marked improvement in attainment in the G482 external examinations, an increase from 43% to 57%. This was despite the increase in difficulty in the G482 module. Nik scored the highest marks on the qualitative analytical problems.

At the end of the first intervention, evidence from both video data and his examination script show a marked shift in approach. Nik undertakes an initial exploration of the problem by reading and underlining key terms and then proceeding to extract the data explicitly. There is modelling of the scenario and highlighting of the domain concepts. An improvement in mathematical procedures is reflected in reduced error rates when performing algebraic manipulation of equations. From a collaborative perspective, Nik assumes the main role of scribe, distilling the group discussions and agreed solution steps. The increase in his self-efficacy is notable as is the possession of a substantial problem-solving schema as demonstrated by clear conceptual knowledge.

Exit data for Nik showed the adoption of a novel approach on the initial exploration, namely use of task-specific self-efficacy to plan the task and manage the time. For problems with higher confidence ratings, consistent progress from problem statement to the solution was evident. Still in some cases with little developed schemata, it can be argued, Nik lapses back into a trial-and-error approach with little progress towards the solution.

The argument to buttress the claim that the shift observed in Nik was due to the change in the learning context to collaborative in steeped in Vygotsky’s (1978) work. The language used during the CGPS is eventually appropriated by Nik and group expectations to regulate behaviour to ensure individual accountability eventually passes into self-regulation. In addition, the initial cooperative approach confined students to specific roles for various tasks, requiring individual accountability, and provided opportunities for the development of the metacognitive skills.

There are no incidents of social loafing during the CGPS in the second cycle. The shift to a cooperative approach meant role assumption for individual group members. These roles were rotated.

In addition, I adopted an `open door´ policy for consultations, provided immediate data based positive feedback on performance and allowed for flexible times for CGPS sessions outside curriculum hours. Nik was given responsibility to manage the group in most cases. It can be argued that these strategies to create positive group learning experiences provided a context that suppressed the generative mechanisms of social loafing which sustained poor academic attainment for Nik.

5.3.5 Summary in response to RQ2

Exit data from CGPS show a high level of collaboration correlated with high attainment. The group scored 80% in this joint exercise. There is evidence of establishing and maintaining a shared understanding throughout the whole discussion. The joint problem space is co-constructed with all the students participating and assuming different roles. The task is jointly planned with students deciding on which questions to start with, allocating these questions high confidence ratings – an indication of high self-efficacy. In addition to establishing group efficacy, this approach is used as a time management strategy. Repairs are collectively done with collaborative argumentation at the centre of the repairs. There is constant monitoring of progress and individual contributions. The group demonstrated a higher level of positive interdependence, a marked shift from the entry data.

High attaining students like Jamal have their contributions analysed and criticised, resulting in a better understanding of the problem. Students establish and maintain different roles. For example, in addition to proposer, Nik assumes the role of scribe while Jamal assumes the manager’s role and Sue is largely a critic. Mik constantly monitors the progress and contributes in instances where repair is needed. All the students’ conversations build upon each other’s contributions and are within the initially constructed JPS. Students contribute to the problem-solving process through adding, explaining and negotiating the shared understanding. There is evidence of argumentation, collaborative completion and repairing of deficits in shared knowledge. There is a high level of individual accountability where students assume different roles and take part in the formulation of action plans and their execution.

A shift towards metacognitive processing is evidenced by a more consistent and constant evaluation of work progress towards a solution (Schoenfeld, 1983, 1985, 1987; Smith & Goodman, 1984; Veenman & Verheij, 2003). Evidence is found in the individual protocols as well as the CGPS exit data. There is detection and correction of comprehension failures (Ferguson-Hessler & de Jong, 1990). There are a number of incidents where strategic monitoring followed by a change in decision occurs. There is evidence of meaningful self-directed speech and questions that echo metacognitive processing in all the students. Compared to the entry data, the evidence suggests the triggering of metacognitive processes during problem solving.

A notable shift in cognitive processing is evidenced by an increase in attainment in both external examinations and written tasks. There is increased automation with mathematical procedures and deployment of heuristics. Students adopt a range of strategies including heuristic use, modelling of the problem statement and working backwards to verify solution steps. There is evidence of use of cognitive load-reducing strategies like data extraction and drawing diagrams, reduced error rates, adoption of efficient problem-solving strategies, e.g. modelling of scenarios, more time allocated to qualitative analysis of the problem, i.e. orientating and planning and automation of the problem-solving process as evidence of schemata.

Summarily, the intervention process produced a shift in all the students, but for different mechanisms. All four students demonstrated a deliberate, well-planned deployment of strategies aimed at reducing cognitive load through use of models and extracting data. The students use heuristics, i.e. they study the problem, extract the data and model the problem, establishing relations between quantities for the specific scenarios in the form of equations and the substitution of data in the final equations. However, there are a wide range of scenarios regarding qualitative analytical problems, with Sue showing a minimal progress limited to extensive writing and stating the physics concepts involved through to Nik who engages in planning of the solution and establishing the physics relations for causal exploration. There is evidence of automation for familiar processes like algebraic manipulations in all students.

The explicit teaching of problem-solving strategies through collaborative group problem solving shows a strong positive correlation with increased cognitive-metacognitive processing. The marked positive shifts in collaborative competences, cognitive competences, metacognitive processing and increased self-efficacy are positively correlated with attainment in problem solving in physics.

In response to RQ2, the study can claim that the shift in approach to problem solving was produced by the intervention, which required a shift in the pedagogic approach to problem solving. Students had studied the G481 module with the traditional approach, with problem-solving strategies embedded in the teaching. The intervention brought to the fore clear strategies that responded to the specific nature of the problems encountered in GCE-physics, developing these within a collaborative context. The results of this intensive study resonate with most findings on the impact on problem solving of explicit strategy instruction.

5.4 A critical realist interpretation of the results

Explanations, from a critical realist perspective, are not achieved by simply estimating parameters of generic statistical models, but by developing generative models that explicate the mechanisms at work (Hauser, 1976; Boudon, 1998). Only by understanding the whole chain of situational, action formation and transformational mechanisms, can we make sense of the observed macro-level relationship (Coleman, 1990; Hedström & Swedberg, 1998). We must seek to identify the situational mechanisms by which social structures constrain individuals' actions and cultural environments shape their desires and beliefs describe the action-formation mechanisms according to which individuals choose how to act, singling out transformational mechanisms by which individuals, through their actions and interactions, generate various intended and unintended social outcomes.

Mechanisms consist of entities (with their properties) and the activities that these entities engage in, either by themselves or in concert with other entities. These activities bring about change, and the type of change brought about depends upon the properties of the entities and the way in which the entities are organised spatially and temporally (Hedström, 2005). A mechanism for behaviour is a complex system that produces that behaviour by the interaction of a number of parts, where the interactions between parts can be characterised by direct, invariant, change-relating generalisations (Glennan, 2002).

The findings of this study suggest that the traditional pedagogic approach to physics learning, low take-up of GCE-level physics, very low pass rate with no pupils not continuing to GCE-A2 level physics and non-existence of support networks within the science or physics department summarised the context which sustained the mechanisms, leading to low success in physics problem solving. The initial data showed poor attainment, inadequate collaboration, low self-efficacy and poor cognitive and metacognitive processing. Following Hedström's argument (Hedström ,2005), the knowledge that there are mechanisms through which explicit strategy teaching through collaboration influences success in physics problem solving supports the inference that explicit strategy teaching through collaboration is a cause of success in physics problem.

Despite the findings of this study that seem to reflect existing findings on problem solving and possible pedagogies, the interpretations are constrained by other circumstances which are the subject of the next section.

5 Limitations of the study

The interpretations of the findings of this study are constrained by the following: sample size, the measures considered for success in physics problem solving, the problems used in the research, the duration of the research and the data analysis procedures. The following paragraphs will briefly discuss how each factor contributes to constraining the depth of data interpretation.

While sampling is a crucial element of study, there is no clear cut answer as to how many students should have made the sample; this depends on a number of factors, e.g. purpose of study, nature of the population under scrutiny, the level of accuracy required and whether the research is qualitative or quantitative (Cohen et al., 2011). For this study, despite the intervention being applied to the whole group of 10 students, only four students who had shown commitment to continue to the second year of their GCE-A level physics study were considered for analysis. This purposive convenience sampling was adopted because it was considered to allow for strong internally valid and credible conclusions (Kemper, Springfield & Teddlie, 2003). Despite an interest in the specific findings for the group involved, the challenge posed by such a small sample is on the reduced generalisability of the findings. The argument in favour of a small sample is the possibility of an in-depth exploration of the mechanisms through which success in problem solving is triggered by such an intervention. This would not be possible if more participants were used due to the amount of data generated and the amount of work and time involved in data processing.

With the qualitative methodology adopted for this study, the focus was not on the generalisability of the findings; however, if the findings can be replicated for other groups then this would be a bonus! The sample allowed for the generation of thick descriptions (Onwuegbuzie & Leech, 2007) and provided insight into unique cases. Without wanting to claim too much, there is no evidence to suggest that these findings are unique to this situation (i.e. cannot be generalised) and are not typical of a large proportion of GCE-A level physics students in the UK.

The literature on the possible mechanisms that must be triggered or suppressed for successful problem solving goes beyond that discussed in this study. In addition to self-efficacy, possession and the timely and accurate deployment of cognitive and metacognitive strategies, and collaborative competence, success in physics problem solving depends on conceptual understanding and motivational factors. The study could not isolate or measure the extent of the impact of the other two factors, conceptual understanding and motivational factors.

This study, steeped in critical realist ontology, had the prime focus of analysing the data for mechanisms rather than outcomes (Pawson, 2006); however, this approach, still in its infancy, still faces resistances in other circles, warns Robson (2011). This is to some extent due to the lack of a clear and conventional way to analyse the data as compared to quantitative data (Robson, 2011). The transcription process for the videos is subjective to a certain extend as only issues that were deemed to be relevant to the study were transcribed. The qualitative content analysis approach for coding the protocols required the construction of coding frameworks. For the purpose of dissemination of the findings, the coding must be capable of being shared and this brings to the fore the importance of inter-coder reliability.

To increase the reliability of the coding process, the frameworks were derived from the literature. Checking for the reliability of the qualitative data framework ensures consistency across time and people. I chose three data samples and coded them using the devised coding scheme on three separate occasions with at least two weeks apart. I used the percentage measure of coefficient. In the literature there is no consensus on a single 'best' coefficient to test inter-coder reliability (Lombard et al., 2003). However, I cannot confirm inter-coder reliability beyond discussions with my supervisor; hence I cannot ascertain if my data coding will not be significantly different if others were to code the same data.

Literature reviewed on QCA suggest assessing reliability through consistence by comparing coding across persons or across points in time. Quantifying this consistency requires calculating a coefficient of agreement through inter-rater or intra-rater reliability. As a sole coder in my research study, I assessed how I coded the same units at two different points in time. For the chosen samples for coding, coded with at least four weeks apart from the first coding, the intra-rater reliability gave an agreement above 90 %. I applied the following computation suggested by Mertens (2010): Percentage Agreement = Number of agreements / (agreements + disagreements) x 100 %.

However, in qualitative research, the reliability is associated with low inference descriptors- giving verbatim accounts of what students say and do rather than researchers reconstructing the sense of what is being said or done, argues Silverman (2014). In my view this numerical value, intra-rater reliability, didn't lend much weight to the reliability of this qualitative study. I concur with Bazeley and Jackson (2013) and Schreier (2014) on that the clarity of the analysis carries more weight than this quantitative measure of reliability. In explaining how the coding system was developed, the reasons behind my conclusions and how I consulted my supervisor, another person familiar with the research, I lent more reliability to my coding process than in calculating the numerical justification with intra-rater reliability.

5.6 Implications for research

Most of the research which informed this study was based on a positivist perspective, an empiricist quasi-experimental approach with a focus on effects rather than processes (Larkin & Reif, 1979; Chi, Feltovich & Glasner, 1980; Larkin, McDermott, Simon & Simon, 1980; Huffman, 1998; Chi & Vanlehn, 2007; Selcuk et al., 2008). However, these studies provided a guideline on problem skills that can be assessed to indicate a shift in competence in problem solving.

This study adopted a model suggested by Jonassen (2011), extending it the Minnesota model. Few, if any studies, have combined the three frameworks of information processing, sociocultural theory and social cognitive theory to study physics problem solving. Jonassen's model argues for strategies that allow schema development to facilitate near and far transfer analogical comparison, an exploration of causal relationships, questioning to support problem solving, modelling problems, argumentation, scaffolding and metacognitive regulation during problem solving. The research methodology, action research, heeds the call to extend research on physics problem to real classrooms situations (Hestenes, 1987).

Further research studies can focus on the mechanisms that are triggered and suppressed by explicit instruction of problem strategies. The quest is to answer the question, "What is it with strategies instruction that produces a positive shift in competence in problem solving?" Further research must interrogate the scientific rigour and transferability of studies that focus on outcomes rather than processes. As a word of caution, Proctor and Capaldi (2012) argue that the explicit teaching of cognitive strategies can lead to fixation with rules and short-sightedness on solutions.

5.7 Implications for practice

The study supports the argument for a pedagogic shift in the curriculum, pedagogy and assessment for GCE physics. The GCE-A level curriculum (OCR-GCE A level-H158/H558) identifies *problem solving* as one of the six key skills to develop. However, very little literature exits as to how this skill should be taught by the teachers, with students relying on standard textbooks and other materials with worked examples. The recent changes in the A-level curriculum have focussed on structure and nature of assessments. The shift from modular courses to linear, two-year courses, to put more emphasis on the mathematical aspect of science, has not done much to remedy this situation (Ofqual, 2014). There is evidently a lack of consistency between policy and practice that filters down to the classroom level. This study didn't look at how this approach to problem solving is treated in post-graduate courses for preparing physics teachers. Little can be done by teachers in terms of policy but at a classroom level, a pedagogic shift to CGPS problem solving can be adopted.

Secondly, assessments must include problems that encourage the development of problem-solving skills, both cognitive and metacognitive. This will require teachers to develop context-rich problems. In assessing students' progress, the data and feedback must reflect individuals' competences in the necessary problem-solving skills like initial qualitative analysis of the problem and modelling the problem state.

To help students develop their own metacognitive skills during problem solving, instruction can include a problem-solving framework which makes explicit the metacognitive processes that are involved in the form of metacognitive prompts. Students must be provided with and facilitate opportunities for students to make their own metacognitive processes explicit through activities like peer teaching. Metacognitive processes are largely implicit; hence, explicit labelling of metacognition for students should be part of the modelling process by the teacher. The discussion of metacognitive processes must be made part of the everyday discourse of the classroom to help foster a language for students to talk about their own cognition.

Finally, it may be helpful for students to have sessions when they video record their problem solving and assess this against the cognitive strategy criteria and the criteria for collaboration.

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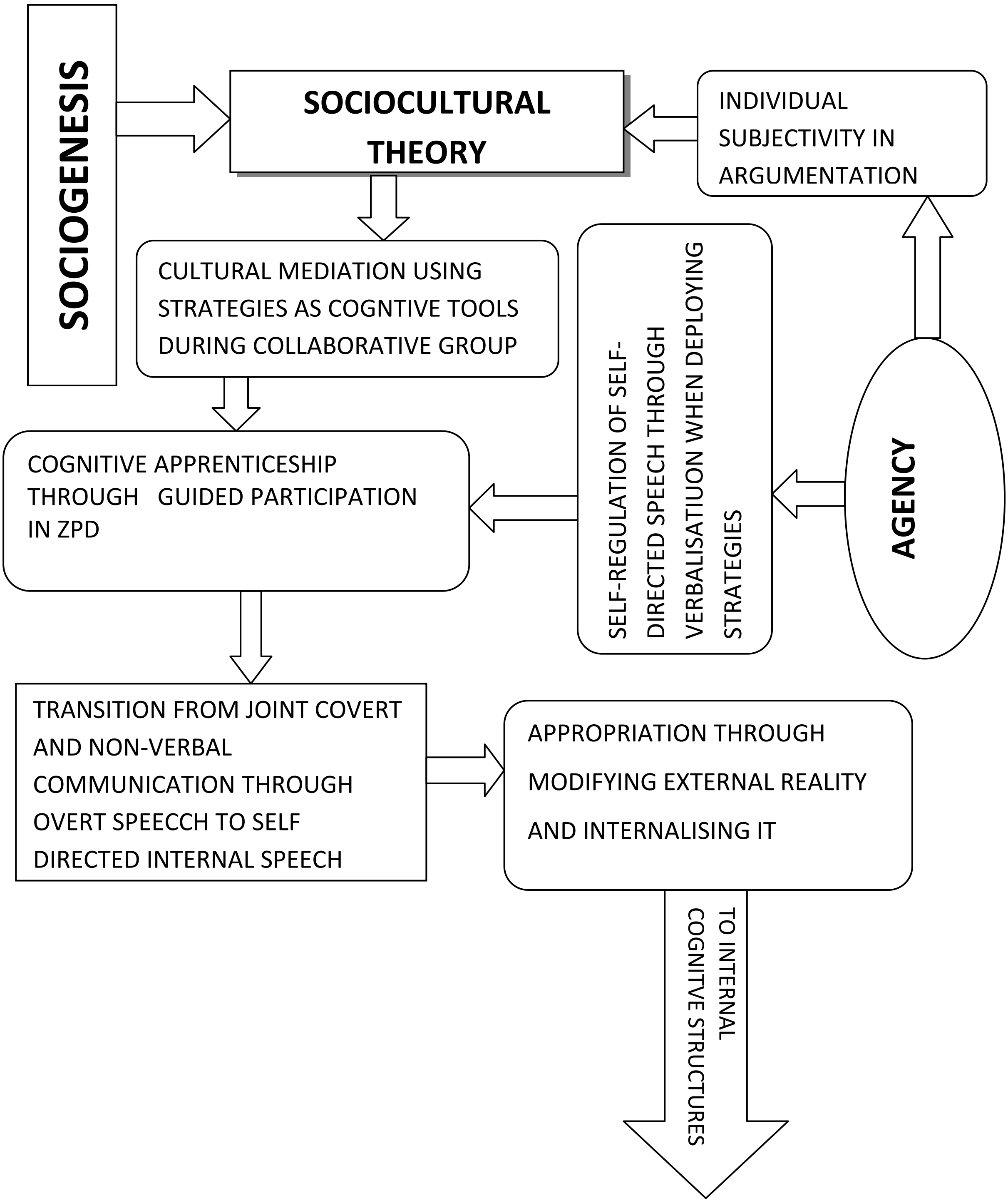
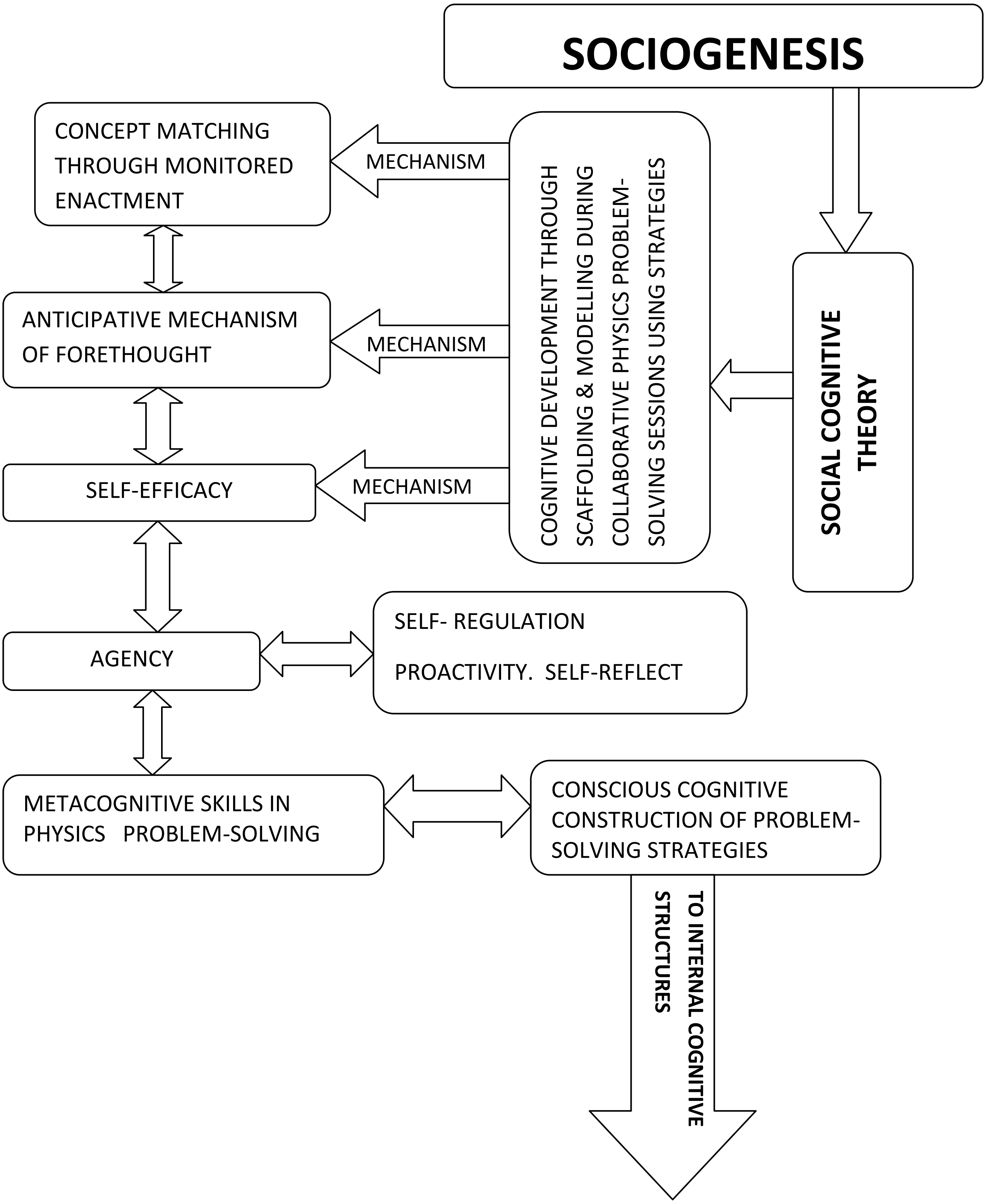
APPENDICES

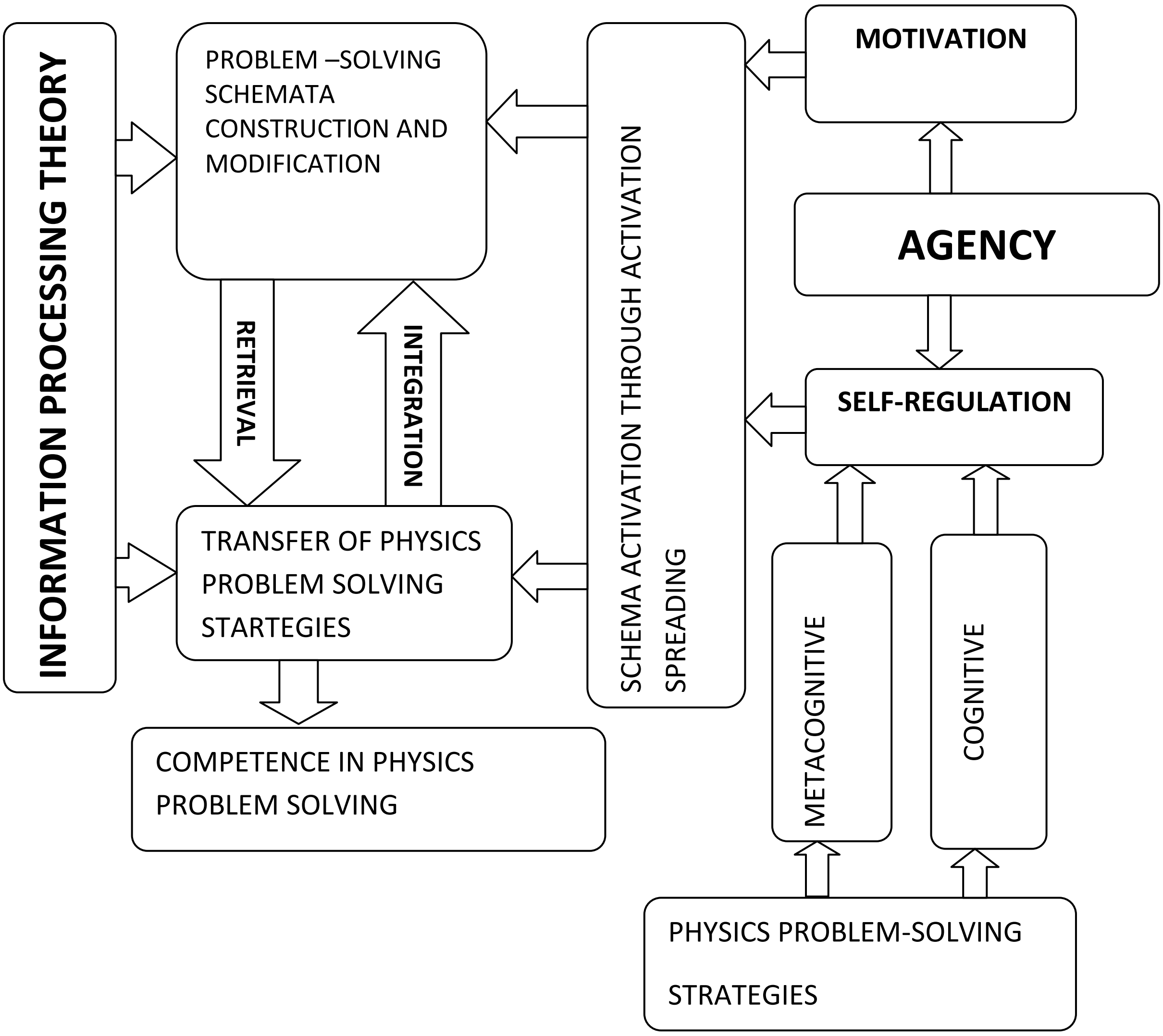
APPENDIX 1: Sociocultural theoretical framework for explicit instruction of problem solving strategies through CGPS



APPENDIX 2: Social cognitive theoretical framework for explicit instruction of problem-solving strategies through CGPS



APPENDIX 3: Information-processing theoretical framework for explicit instruction of problem-solving strategies through CGPS



Appendix 4: Approach to effective problem solving

Qualitative/Essay Problems and Quantitative Questions	**Metacognitive cues**
Focus the Problem • Read, study and understand the question. • **Underline** key aspects. • Construct a mental image of the sequences of events described in the problem statement. • Sketch a picture that represents this mental image; include given information. Which fundamental physics concepts could be used to solve the problem? • What information is really needed? • Should you make any approximations?	• What is the problem about? • What am I trying to do here? • What do I know about the problem? • What information is given to me/us -how can it help? • Have i solved a similar problem before?
Describe the Physics • Establish what the key task demands are. • Construct diagram(s) to show important aspects of the phenomenon in question. • Make sure all symbols representing quantities shown on diagram(s) are defined. • What quantities are needed to define the problem mathematically using the approach chosen? • Which symbols represent known and unknown quantities? • State mathematical relationships from fundamental concepts and specific constraints.	• Do I understand the problem requirements? • Is the problem familiar? • What physics domain/s is the problem? • What are the key principles? • Can I model the problem? • Is the information sufficient?
Plan the solution • For descriptive7essay type problems, make a rough plan with specialist terms, equations to explore causal links, diagrams or graphs to model scenario. • Construct specific equations to represent specific physics concepts. • Substitute specific variable symbols into general equations; drop variables with zero value. • Outline how to use the specific equations to determine the target variable or explore the causal links.	• What is my solution strategy? • Can i break down the problem into sub problems? • Can i analogically the problem to a previously solve one? • Am I using a plan /strategy? • Do I need a new plan/strategy? •

Execute the Plan **For qualitative (essay-type) problems,** use the draft to a write a clear, concise and logically sequenced response. Show the causal links where required and support the argument by using equations and graphs where necessary. **For quantitative problems**, isolate the unknown quantity and isolate the target variable, check each term for the correct units and do some dimensional analysis, Compute the value for the target variable and estimate the final value and then *calculate target quantity and answer the question*.	• Am I on the right track? • Am I closer to the goal now? • Is your answer properly stated? • Is my progress consistent with the time allocation?
Evaluate the Solution • Evaluate the answer against the problem demands and the allocated marks • Check that solution is properly stated; it Is reasonable and is complete**.**	Is the answer reasonable? Is the answer complete? What worked? What didn't work? What can I do different next time? Can i use a different solution path to verify my answer?

Appendix 5: Script coding for the G482 external examination script- Physics

		QUESTION TYPE	Part Question	Max Mark	Candidates				Executable categories																				
					Sue	Mik	Nik	Jamal	Focus the problem							Plan the solution						Execute the Plan							
									1	2	3	4	5	6	7	1	2	3	5	6	7	1	2	3	4	5	6	7	8
1		QL-AN	N	2	■ 2	■	■	■											■			■							■
2	a	QL-B	N	2	■ 2		■	■			■																		
	B i	QN-CL	N	2	0	■	■	■					■				■						■						■
	ii	QN-C	N	2	0	■				■	■		■			■			■			■	■					■	■
	iii	QL-AN	N	1	0	■		■											■			■							■
	iv	QL-AN	N	1	0			■																					■
3	i	QN-CL	N	1	■ 1	■	■	■		■								■				■	■						
	ii	QN-CL	N	3	■ 3	■	■	■																					
	iiii	QL-AN	Y	3	0			■			■		■						■		■					■	■		
	iv	QL-B	N	4	1			■			■	■							■							■	■		
4	aA	QL-B	N	1	■ 1	■		■			■								■										■
	b	QL-B	N	1	0			■		■				■					■			■	■						
	c i	QL-GR	Y	3	■ 3	■	■	■		■				■					■							■			
	ii	QN-GR	Y	3	■ 3			■						■	■			■				■							■
	iii	QL-AN	y	2	0				■	■	■					■	■					■	■						
5	a	QL-B	y	1	■ 1	■	■	■																					
	bb	QL-B	Y	3	1			■	■				■	■		■			■		■					■	■		
	C i	QL-AN	N	1	■ 1	■	■	■	■		■					■										■	■		
	C ii	QL-AN	Y	4	4			■	■										■		■						■	■	
6	a	QL-BR	N	1	■ 1	■		■	■			■					■											■	
	b i	QN-C	N	2	■ 2	■		■		■		■				■	■	■			■	■	■		■				
	b ::	QN-C	Y	3	0					■											■	■			■				
7	a	QN-C	N	3	0	■		■	■		■		■				■				■	■					■		
	b	QL-B	N	1	0				■				■				■									■	■		■
									■				■				■									■	■		■

Appendix 6: Problem-solving protocol for end of first intervention cycle 2: Mik

Date: July 12, 2013

	Action **+** *verbalisation* **+ commentary**	**S E**	**METACOGNITIVE**					**COGNITIVE**				
			A	B	C	D	E	A	B	C	D	E
00:00	reads the question *" ... state in words, Newton's Second Law ... "*		■									
	Verbalises the answer, repeats it			■		■						
▼	**Must have written a rough draft to aid with planning, including wiring the equation somewhere**.											
01:00	*"... so force ΔP is equal to $F\Delta t$ .. so force is equal to $\Delta P/\Delta t$ ..."*	■		■					■			
▲	Writes a definition from the equation , off the top his head	■			■					■		
	Good retrieval and clarity of physics concepts				■							
02:00	Moves to question 1(b)											
	"... so I choose that direction to be positive ..." draws reference line and assigns a positive direction			■	■			■				
02:30 ▲	*"... The data is ....the M_A is 3.0 kg* **..**" proceeds with data extraction . **Deploys a heuristic approach for momentum and collision problems**			■				■	■			
03:00	*"... if they have a common velocity , $V_A = V_B = V$ ... "*			■						■		
03:30	*"... So using the Law of conservation of momentum ..."* Writes the correct equation for the conservation of momentum and applies the chosen convention. $M_AU_A - M_BU_B = M_AV_A + M_BV_B$				■				■			
04:00					■							
04:30					■					■		
	Proceeds to make v subject of the formula				■						■	
	Substitutes data into equation				■						■	
05:00	Calculates and checks data entry				■	■					■	
06:00	Checks working and writes answer	■				■					■	
▲	**Good progress with automation of algebraic manipulations. Automation suggests presence of schema; data extraction reflects working**											■

	memory load reducing strategies and there is evidence of good progress.											■
06:30 ▲	Proceeds to the next section, pauses and writes answer *"... So it's in the positive direction ..."* **Good progress on time vs. attainment**.					■						
	Reads part (ii) *" ... determine the impulse of the force* **... "**		■									
	" ... so impulse is delta P , which is change in momentum **...**"			■						■		
	Writes equation $\Delta P = F.\Delta t$				■						■	
07:00	*"... so impulse, change in momentum will be ... "* pauses		■								■	
07:30	*"... mV-mU* ..."			■								
▼	*"... Force is equal to m x a ... "*											
	Deviates from a heuristic approach and embarks on a trial and error path.											
	"..so impulse is m x a x t **...** *"*			■								
	Pause and checks					■						
08:00	" ... we don't have acceleration , so we can't use this					■	■					
▲	*"... ΔP is equal to mV- mU... so to find the final momentum ... "*				■							
	Monitoring results in change in approach and a path to the answer. Modelling scenario after impact would have helped.				■							
08:30	Calculates the impulse and the direction	■			■							
	Reads next question *"... explain, using Newton's third law ... "*		■									
10:30	*" ... impulse of a force is equal to...equal to..." pauses "... force x time ... "*		■									
	writes a rough draft on the side $\Delta P = F..\Delta t$			■								
▲	**A good strategy for answering qualitative questions. A rough draft to aid a logical sequencing of facts with a scientific rigour.**								■			

11:00	*"... therefore impulse by A should be equal to impulse by B at the point of impact ... "*			■								
▼	**Should have drawn the diagram, shown the two forces and used equations to justify assertion. Lacks scientific rigour.**				■				■			
	"... so force of A on B should be equal to force …minus force of B ... "				■				■			
11:30	*"…. so force provided by A is the same as provided by B at the point of impact …."*			■					■			
	Proceeds to write final answer after the draft and planning.				■							■
13:00	Finishes writing answer, checks and moves on to next question.	■			■	■	■					■

<u>Appendix 7</u>: Problem-solving protocol for end of the second intervention cycle - Mik

<u>Date</u>: October 23, 2013

	Action **+** *verbalisation* **+ commentary**	**SE**	**METACOGNITIVE**					**COGNITIVE**				
			A	B	C	D	E	A	B	C	D	E
	Student is given a time limit of 30 minutes											
00: 0	Reads the questions. *"... I will start by doing my confidence ratings…"* Student starts assessing his self-efficacy at each problem using the confidence ratings. **Evaluating knowledge -a metacognitive process.**		■	■			■					
	Verbalises			■								
00:30	*"… I will give this 90 ... "*	■		■			■					
	Flips through *"… question 2……ok … "* scans the question *"... it's about circular motion and little on gravitation ..."*			■				■				
▲	**Good strategy of confidence ratings. Identifies problem domain and decides on probability of success**											
01:00	*"… It's just this one page. So will give that 90 … "*	■		■			■					
	Flips through the pages , scanning the questions											
01:30	*"… then question 5 is about thermal physics …and it's a lot more qualitative ...so give that 70 ...***"**…student self-assesses and identifies an area of weakness, qualitative problems.	■		■			■					
▲	**This phase of planning involves picking relevant cues and possibly linking them to already existing schema and evaluating the success of the transfer process for the novel situation.**											
02:00	Moves back to first problem, rated 90. *"… State the principle of conservation of linear momentum …"* reads question slowly.		■									
02:30	Verbalises slowly to aid retrieval			■								
03:00	Moves to next part and reads *"… explain what is meant by an inelastic collision …"*		■									
	Verbalises the answers and proceeds to write the answers down beginning with part (ii)							■				■
▲	**Student automatically starts with an easier part (ii) and proceeds to part (i)**. Good progress				■							
03:30												
04:00	Progresses to next question. reads and pauses after					■						

	a few seconds					■						
04:30	*"... so first draw a reference frame and say objects moving to the right have positive momentum ..so object A moving to the right has positive momentum ..."*				■			■				
▲	*"... so* M_AU_A*-*M_BU_B *=* M_AV *+*M_BV *...positive since they are moving in that direction ... "*				■				■			
	An algorithmic approach to momentum questions				■							
05:00	*"... since there is a common V in the second part you can say V(*M_A *+*M_B*) ... "*				■					■		
	"... so to re-arrange..." re-arranges for V.				■						■	
05:30	Picks calculator, substitutes values direct from question				■							
06:00	*" ... That's 1.33 recurring ...to 3 significant figures ... "*				■						■	
▲	**Good progress. In-depth scientific knowledge on momentum. Good mathematical skills and effective use of heuristics**				■							
06:30	Reads next questions		■									
	"... show that this collision is inelastic ..."		■									
	"... Inelastic collision will not conserve kinetic energy, so we should find the kinetic energy and show that the kinetic energy is not the same before and after collision ..."			■					■			
07:00	*"... so the kinetic energy of the block at the beginning will be* $\frac{1}{2} m_A u_A^2$ *and final energy will be* $\frac{1}{2} m_A v_A^2$ *... "*				■							
	Proceeds to calculate the solution.				■						■	
07:30	*".. . equal to 10.8 J and final kinetic energy is ... "*				■						■	
	Calculates values "... you only got 2.13 J ..."				■							
	"... so final kinetic energy is 2.13 J which is not the same as the initial KE ... " writes 10.8 J is not equal to 2.13 J										■	
08:00	*"... energy is lost and collision is inelastic ..."*				■					■		■
	Reads next question on hovering helicopter. **Takes a long time for orientation, problem is not familiar.** **Requires far transfer**		■									
08:30 ▲	*"... so first get down the data, radius of the circle is 5 meters, speed of the air going downwards is* $12ms^{-1}$ *... "* Continues to extract data			■				■				
	Relies on a heuristic approach to solve an unfamiliar problem.			■								
09:00	Finishes and reads question again					■						
	"... they say the descending air occupies a cylinder, a cylinder has a radius of ..."		■					■				

09:30	Models the cylinder by drawing				■			■				
	Good use of models				■							
▲	*“... so if the density, which is mass/ volume ...so what we should do is find the volume of the cylinder and multiply by the density to get the mass ... ”*			■					■			
10:00	*“... the volume of the cylinder will be ... ”*				■						■	
10:30	Substitutes data to calculate the volume				■							
	“... and here the metres will just cancel out and will remain with kilograms. ...” **Good use of units to monitor accuracy of algebraic manipulation.**				■	■					■	
11:00	Pauses and checks work					■						
▲	*“... so* πr^2 *will give you the circle the height will be 60m...”* corrects the initial value on the mode ...”					■				■		
	Good monitoring of work results in change in data. Use of a working backward strategy.											
11:30	*“... multiply by the density which gives 6126...that’s around 600 kg ...”*				■						■	
12:00						■						
	Reads part (ii) *“... Calculate momentum ......”*		■									
	“... So momentum is equal to m x V , the mass of air is 600 kg and the velocity is $12ms^{-1}$ *...so multiply 6126 by 12 ... “*			■					■			
	Calculates. *”... that’s 72 000* $kgms^{-1}$ *...* 7.2×10^{4} *...“*				■						■	
13:00	*“... calculate the force provided by the rotor ...”*		■									
	“... so Newton’s Second Law ....$F=\Delta P/\Delta t$*.... so* Δt *is 5 seconds ... “*			■	■							
13:30	Calculates the values *“...that’s 14 400 N ... ”*				■					■		■
14:00	Reads the next question *“...the mass of the hovering helicopter* **...** *”* pauses											
14:30	*“... so the force provided by this helicopter is to propel the air downwards ...”* pause **“ ...** *this also keeps it up ...that means the force propelled will also be equal to its weight ... ”*		■							■		
	“... so you can say mg =14 400N...so you simply divide that by 9.81 to get the mass ... ”			■						■		
15:00	Calculates ... *“ ... mass comes out as 1467.889908* **... “**				■						■	■
	Converts solution to 3 significant figures				■						■	■
												■
	Good progress **Student scored 27/30 in 35 minutes**											

APPENDIX 8: Problem-solving protocol for end of cycle 2-Exit- for Sue

<u>Date</u>: October 23, 2013

	Individual action, *verbalisation* and **commentary.**	**S E**	**METACOGNITIVE**						**COGNITIVE**				
				A	B	C	D	E	A	B	C	D	E
00:00	Student looks through all questions, writes confidence ratings for the questions. **Metacognitive evaluation of knowledge with respect to set tasks. Planning strategy involves rating all problems for probability of success.** Chooses problem with a confidence rating of 100. ***"...** a particular collision ...two objects in inelastic collision ..."*							■					
00:30				■				■					
01:00 ▲				■									
01:30				■									
02:00		■		■									
02:30		■		■									
03:00	Underlines the word <u>inelastic</u>...				■								
03:30	*" ... Momentum is conserved, kinetic energy isn't conserved ...* **"** writes answer and proceeds to question 1 (b).					■				■			
04:00	Reads question 1 (b), underlines keywords *"... so that will be positive ..."* draws a reference frame and labels the positive direction.			■					■				
					■								
04:30	Continues to read question, underlines key data. *" ... calculate the loss in kinetic energy during the collision ... "*			■					■				
	" ... so we have to find the initial and final kinetic energy ... "				■		■		■				
05:00	*" ... so mass is 0.006 kg, initial speed u ..."* extracts data.				■				■				
▲	**Deploys a heuristics approach** *" ... initial KE is ½ mu^2 ... "*					■					■		
05:30	Picks calculator and computes the data *"... that will be ... 4.32J ... "*					■						■	
	Writes the answer down *"... and then final kinetic energy is ½ mv^2 ... "*					■					■		
	Writes the equation and proceeds to substitute values.					■						■	
06:00	**"** *... that is 2.43 J ...* **"**					■						■	
06:30	Stops, checks the answer, and reviews the calculations.						■						■
							■						
	Reads slowly *" ... so the final kinetic energy ..."*			■			■						
	"... 2.43 minus 4.32 is equal to ..." picks calculator and proceeds to calculate. *"... That*					■					■		

	will be 1.89 ..." fills in answer.					■					■		
07:00	Reads question slowly, checks answer in silence.						■	■					■
	" ... mmmm right ... "	■						■					■
	Reads next question *" ... magnitude of the average force ... "* underlines <u>average force exerted</u> *" ... that will be ... "* pauses			■									
07:30	*" ... F = ?... "* writes			■									
	"... F times delta t equals to delta p... $F\Delta t = \Delta P$....delta P is ... "				■				■				
	Pauses						■						
	".. . and delta P is ..." points at diagram,					■				■			
	writes equation $\Delta p = mV - mU$.					■					■		
08:00	Proceeds to substitute data					■						■	
	Calculates the values					■						■	
08:30	Writes 0.54 at bottom of page. **Reducing cognitive load in working memory**. Proceeds to make calculations.					■							
	"... minus 1.26 ... "												
09:00	*"... therefore $F\Delta t = 1.26$ ... "* pauses and re-reads the question. **Orientating and monitoring problem comprehension.**			■			■						
	"*... delta p over delta* t ... *"* pauses						■				■		
	.. proceeds to calculate					■						■	
	" ... 8.4 ... "					■						■	
09:30	Proceeds to next question												
	" ... The magnitude of the average force..." Reviews the previously solved questions to get hint. *"... That will be ... "* pauses, scans the previous answers again.			■									
	" ... minus 8.4 ... "					■				■			
▲	**Recognises it's a part question and implicitly applies Newton´s Third Law, an automated operation due to existence of schema**												
10:00	Scans the answer , removes the minus sign						■						
▲	**Good monitoring results in change of answer, use of set reference frame**												
	Reads next question			■									
10:30	Attempts problem (a recall problem). " *... I think the solid ...mmm ...*" pauses ...." ... no... ." proceeds to erase						■						
11:00	Checks confidence rating (50), changes the rating to 30 and moves to next problem…monitoring results in lowering of						■						

	confidence rating level. **Evaluates knowledge**.						■						
11:30 ▼	Attempts a thermodynamics question, writes about Boyle´s law rather than the Kinetic Theory. **Inadequate knowledge leads or lack of schema leads to poor problem comprehension.**		■										
	Abandons strategy of solving those problems with high confidence ratings briefly												
12:00													
12:30													
13:00	Proceeds to next page ...scores no marks on question.												
	Reads question, underlines , continues to read		■			■	■						
▲	Skips one part, a qualitative part and proceeds to a quantitative part.		■				■						
	Good strategy to save time but evidently, there is lack of appropriate strategies in tackling qualitative questions.												

Appendix 9: Problem-solving protocol for end of cycle 2-Exit for Nik

Date: October 23, 2013

	Individual action, *verbalisation* and **commentary**	SE	METACOGNITIVE					COGNITIVE				
			A	B	C	D	E	A	B	C	D	E
00:00 ▲	Reads the problem s *"... I am going to jot my confidence ratings ..."* looks at the first question and writes 60 %. **Evaluates scientific knowledge and probability of success on given problems.**	■		■			■					
00:30	Scans question "... 70 ... "	■		■								
01:00	Continues to scan questions and part questions , estimating success rate			■								
01:30 ▲	**A strategy based on self-efficacy aimed at maximising the use of time and gradually working through, gaining confidence, as the problem difficulty rises.**			■	■							
03:00				■								
	" ... I am starting with the one with the highest rating ... " the question is rated 70	■	■									
	" ... the graph is of force and time ...." pauses ...		■					■				
	" ... that's $F.\Delta t = \Delta.P$ *..."* writes down equation on the left side.			■				■				
03:30	*" ... the momentum given to the ball can be found by the area under the graph ... "*				■				■	■		
▲	**Notable progress through to execution suggesting existing schema of this type of problem. Evidence of planning before writing qualitative answer.**									■		
04:00	Writes the solution and checks. Reads the problem statement but fails to comprehend it ...trial and error leads to wrong solution.				■							
06:00						■						
▼	**Student has high confidence and perseveres with the solution but comprehension failure and graphical misinterpretation leads to poor solution. No time monitoring.**	■										
08:30	Moves to question, reads question and picks up calculator. Student attempts a few questions through trial and error.											
▼	**Student abandons strategy and reverts back into trial and error mode. This shift in approach costs valuable time.**											
14:00	Student flips between questions											
	"... I am now moving to a question with a higher rating ... "					■						
	Picks a quantitative question, confidence rating of 60 *"... first I have to list the given data*				■			■				

	... ”				■			■				
▲	**Good strategy, monitoring of progress cut the ‘wild goose chase’ and student adopts heuristic approach and picks a quantitative question.**											
15:00	*“... So kinetic energy is 7.6 x 10 $^{-13}$ J...mass of alpha particle... ”*	■	■						■			
	Proceeds to extract and note down data	■		■				■				
	“...so I need to determine speed...so the equation for kinetic energy is $E_K = ½\ m\ v^2$ ...”	■			■					■		
	“..I re-arrange this.. it will be ... ” proceeds to make v the subject of the formula	■			■						■	
15:30	*“ ... I substitute this ... ”*	■			■						■	
	Proceeds to substitute and converts answer to standard form	■			■						■	
▲	**Reverting to use of heuristics yields 2 marks in 2 minutes. There is evidence of schema due to the degree of automation involved in this problem solving process**											
17:00	*“... That is approximately equal to 1.5 X10 ^{7} ...”.* **Evaluates the solution.**						■				■	
	“ ... My final answer is very similar to this ... ”	■				■						
17:30	*“... second part of the question ... ”* reads question *“...the particles are both charged. Due to this ...they repel ...* **”**		■					■				
	Writes the answer, scores 2/3 marks				■							
19:00	Pauses *“ ... due to electrostatic force ... ”*					■						
	continues to write.				■							
20:00	Reads second part of the question *“...explain how it is possible to calculate the speed ... ”*		■									
▲	*“... the alpha particle has momentum, it loses momentum and the gold nucleus gains momentum ... ”*			■					■	■		
	Good demonstration of scientific knowledge											
21:00	*“... momentum....total momentum is always conserved ....momentum is transferred from the alpha particle ...* **”**			■						■		
	Proceeds to write the second part of the answer. *“.... so the speed can be can be found calculating the change in momentum of the gold nucleus ...”*				■					■		
21:30					■							
22:00	Reads part (iii)		■									
	“ ... First of all I draw a reference frame ... ” draws the reference frame.			■				■				
					■							
	“ ... and data ... ” extracts the data			■				■				
23:00	“...so the formula for this ...” writes a correct law for the conservation of momentum				■				■			
24:00	*“... so alpha particle here is stationary ...which means the initial velocity for the gold particle*				■					■		

	is zero and the final for alpha is zero ... " proceeds to cancel U_B and V_A.				■					■		
▲	**Good qualitative analysis of scenario, logical progression of process and speed. Possibility of existence of schema on this type of problem.**											
24:30	*" ... so we need to re-arrange the equation ... "* re-arranges and solves the equation successfully.				■					■	■	■
	Checks solution and finishes.					■		■				■

APPENDIX 10: Survey of Self-Efficacy in Science Courses – Physics (SOSESC–P) (adapted)[C1]

The Survey of Self-Efficacy in Science Courses – Physics (SOSESC–P), a survey for students to evaluate self-efficacy.
Immediately following the survey is a description of which items are used for calculating scores in each of the four sources categories, as well as an indication of which items were reverse scored.

SOSESC—Physics

Please indicate how strongly you agree with each of the following statements about your experiences *in this course* (including labs, if applicable.)

1: Strongly disagree 2: Disagree 3: Neutral 4: Agree 5: Strongly agree

1.	I received good grades on my written test and exams in this course.	
2.	My mind goes blank and I am unable to think clearly when working on problems in exams.	
3.	Watching other students in class make me think that I cannot succeed in physics.	
4.	When I came across a tough physics problem, I work at it until I solve it.	
5.	Working with other students encouraged and motivated me in this class	
6.	I have usually been at ease in this course.	
7.	Listening to the teacher and other students in problem-solving sessions make me think that I cannot understand physics	
8.	I find the material in this course to be difficult and confusing.	
9.	I enjoy physics problem-solving activities.	
10.	My teacher's demonstrations and explanations give me confidence that I can solve physics-related problems.	
11.	I am rarely able to help my classmates with difficult physics problems.	
12.	My teacher encourages me that I can use physics concepts to understand real life phenomena	
13.	I usually don’t worry about my ability to solve physics problems	
14.	I have difficulty with the exams/tests in this course.	
15.	I am poor at doing other activities to explore physics questions.	

16.	The teacher in this course encourages me to put forth my best efforts.	
17.	I rarely know the answer to the questions raised in class.	
18.	Physics makes me feel uneasy and confused	
19.	I identified with the students in this class who did well on exams/tests	
20.	I get positive feedback about my ability to recall physics ideas.	
21.	I get a sinking feeling when I think of trying hard physics problems	
22.	I learn a lot by doing my physics assignments.	
23.	In this course, I admire my teacher’s understanding of physics	
24.	In-class discussions and activities help me to relax, understand, and enjoy my experience in the course	
25.	My teacher’s feedback discourages me about my ability to perform well on physics exams/tests.	
26.	It is fun to do this AS physics course.	
27.	I can relate to many of my classmates who are involved and attentive in class.	
28.	No one in class encourages me to go on and study science after this course.	
29.	I get really uptight while taking exams/test in this course.	
30.	I can remember the basic physics concepts taught in this class.	
31.	Classmates who are similar to me usually have trouble recalling details taught in class.	
32.	My peers in this course encourage me that I have the ability to do well on class assignments	
33.	I am attentive and involved in what is going on in class.	

SOSESC—Physics Key

	Mastery Experiences ME (10 items)	**Attainment**	1, 15-R, 11-R, 4
		Understanding	22, 8 –R, 7 -R
		Attention	33
		Test taking	14-R

		Recall and recognition	30
	Vicarious Learning (VL) **7 items**	**Attainment**	10, 3-R,
		Understanding	23, 7-R
		Attention	27
		Test taking	19
		Recall and recognition	31-R
	Social Persuasion (SP) 7 items	**Attainment**	32, 16, 28-R
		Understanding	12
		Attention	5
		Test taking	25-R
		Recall and recognition	20
	Physiological State **(PS) 9 items**	**Attainment**	13, 9, 21-R
		Understanding	18-R, 21
		Attentiveness	6, 26
		Test taking	29
		Recall and recognition	2-R