

# Extended Information processing of Technology Education learners during the early phases of the design process

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by

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*Faculty of Education*

*University of Pretoria*

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## Declaration of originality

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*I declare that the dissertation, which I hereby submit for the degree Master of Education at the University of Pretoria, is my own work and has not previously been submitted by me for a degree at this or any other tertiary institution.*

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## Ethical statement

The author, whose name appears on the title page of this dissertation, has obtained the applicable research ethics approval for the research described in this work. The author declares that he has observed the ethical standards required in terms of the University of Pretoria's Code of Ethics for researchers and the Policy guidelines for responsible research.

 	
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## Abstract

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The purpose of my study was to describe the manner in which Grade 9 technology learners typically accessed and used information sources during the early phases of their design processes. I did this by using an Extended Cognition framework to study the internal and external information sources that learners typically accessed and used in a technology learning environment. Theoretically, my study aimed to develop the application of the Extended Cognition Theory in an educational context. In this manner, my study adds to the scarce literature on design cognition in technology education. The methodological purpose of this study was to adapt conventional Think Aloud Protocol methods (TAPS) to investigate groups of learners in their natural technology learning environment. This methodology enabled me to understand the link between theoretical and empirical approaches of design cognition. As such, I was able to conceptualise practical guidelines that could be used by technology lecturers and teachers for the effective facilitation of the early phases of design processes.

The conceptual framework of my study was adapted from empirical studies of expert designers, and is underpinned by the Information Processing and Embodiment theories. I followed a concurrent mixed methods approach and employed a case study design applying pragmatic assumptions. The target population for this study comprised Grade 9 learners based in a low socio-economic region. Eight female participants were purposefully selected and conveniently clustered into three groups: two groups of three participants, and one group of two participants. Data collection therefore consisted of three separately video recorded protocol studies. I was able to elicit the information access and usage activities of the participants by providing them with a design task that I adapted from a prescribed textbook, as suggested for technology by the Department of Basic Education. During the video recordings of the participants' design processes, I was able to collect concurrent verbal, visual and temporal data types. I analysed the data according to a five-level framework, also adapted from the empirical investigations of expert designers.

During my quantitative data analysis, I identified the occurrences of each group of participants' cognitive phases, as well as the occurrences of their information access and use activities during each cognitive phase. On the one hand, problem structuring did not occur regularly. However, during their problem structuring activities, the participants mainly accessed and used instructions contained in the design task and pictures. On the other hand, the participants predominantly exhibited problem solving cognitive phases in which they mainly accessed and used external information sources including pictures and sketches.

During my qualitative data analysis, I traced how the participants transformed their understanding of the design problem and possible design solutions. During problem structuring, the participants accessed information about the users' needs, the design context and design objectives by perceiving and recognising useful information in their design task instructions and pictures. Information use during problem structuring was evidenced when the participants transformed information that they accessed to propose design objectives, constraints and requirements. Accessed information was typically transformed when the participants: (1) Read/evaluated information from the design task; (2) Evaluated the problem/context; (3) Evaluated/Elaborated information about the design objective; (4) Justified a design requirement; (5) Proposed/justified a design constraint; (6) Evaluated/Elaborated available resources in the environment; (7) Elaborated on the design context. During problem solving, the participants accessed information about the function, behaviour and structure of possible design solutions by perceiving and recognising useful information, primarily in their sketches, 3D models and pictures. Information use during problem solving was evidenced when the participants transformed accessed information to propose design specifications and limitations. Accessed information was typically transformed when the participants: (1) Evaluated existing solutions; (2) Proposed design limitations; (3) Modified existing solutions; (4) Proposed/evaluated a design idea; (5) Elaborated on a design idea; (6) Justified ideas; (7) Qualified ideas; (8) Modified previous design ideas.

From the findings of my study, I could develop practical guidelines for current and future technology teachers. These guidelines should help technology teachers to effectively facilitate information rich design thinking during the early phases of learners' design processes. I conclude this study by reiterating that the participants' design cognition was enhanced by the availability of various information sources. This implies that technology teachers play a central role as information providers and mediators. Failure to provide adequate information sources during design tasks might inhibit learners' development of the proficient design skills intended by the technology Curriculum and Assessment Policy Statement (CAPS) document.

**Keywords:** Design cognition, Design Process, Early phases, Ecological psychology, Embodiment, Extended Cognition, Information Processing, Information sources, Technology Education, Think Aloud Protocol Study.

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Opinions expressed and conclusions arrived at are those of the author and may not necessarily be attributed to the above mentioned institutions.

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## List of Acronyms

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<b>CAPS:</b>	Curriculum Assessment Policy Statement
<b>DoBE:</b>	Department of Basic Education
<b>LTM:</b>	Long-Term Memory
<b>LTSM:</b>	Learning and Teaching Support Materials
<b>Mini-PAT:</b>	Mini-Practical Assessment Task
<b>TAPS:</b>	Think aloud protocol study
<b>TE:</b>	Technology Education

# Chapter 1 : Orientation of the study

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## 1.1 Chapter overview

The purpose of this chapter is to introduce the developing status of Technology Education (TE) and the inherent challenges that hamper effective curriculum delivery. This is followed by a description of the research problem, which is related to the limited pedagogical guidelines for facilitating design cognition provided in the technology Curriculum and Assessment Policy Statement (CAPS). Thereafter, the purpose, rationale and aims are stated, together with the resulting research questions guiding the design and implementation of this study. The context of the study and the research methodology are dealt with, followed by an exploration of the key terms used in this dissertation. Finally, an outline of the organisation of the dissertation is presented, concluding this chapter.

## 1.2 Foundations of the study

Design thinking is essentially a cognitive activity that is information-intensive, which is driven by a designer's ability to effectively access and utilise information (Alexiou, Zamenopoulos, Johnson & Gilbert, 2009; Eastman, 2001; Visser, 2009). It is this ability to effectively access and utilise information that contributes greatly to the quality of a design solution, especially during the early phases of the design process (Goel, 1995). During the early phases of the design process, designers typically structure and solve their ill-structured design problems. Design thinking, or design cognition, is furthermore acknowledged as a catalyst for innovative solutions (Brown, 2009; Martin, 2010). Therefore, if we want designers to rise above mediocrity and meet the challenge of becoming innovative thinkers in the forefront of innovation, we should prepare them accordingly in Technology Education (TE). For this reason, technology teacher education programmes should ideally be based on the practice and skills of expert designers (De Vries, 2005; Haupt, 2014; Oxman, 2001).

Researching the design cognition of professional designers is crucial to understanding the cognitive activities of designers, and providing support for the development of design education curricula (Blessing & Chakrabarti, 2009; Lemons, Carberry, Swan, Rogers & Jarvin, 2010). However, there is still a serious paucity of design literature on empirical research into novice design cognition, and on models for researching novice design cognition behaviour (Middleton, 2010; Petrina, 2010; Zuga, 2004). There seems to be a need, therefore, for research that attempts to understand how novice designers engage in designing. This is necessary in order to provide practical guidelines for the training of future technology educators and design practitioners (Goldschmidt & Rodgers, 2013; Haupt, 2014; Oxman, 2001).

Such knowledge, derived from empirical research on novice design behaviour, could feed into technology education programmes and curriculum design and be based on professional design research. In turn, the theoretical underpinnings of design learning in technology could also inform professional design education programmes to support the training of future professional designers (Stables, 2012).

When compared to international disciplines such as science and mathematics, TE as a school subject can still be regarded as relatively new. From its inception in the mid-1980s, TE has evolved to take on many different forms and adopt many different approaches, including craft-based, design-based, vocational, high-tech, computer-focused, multidisciplinary approaches, and technology as an applied science (De Vries, 2006, 2012). Hence, a firm research base, a subject philosophy and academic boundaries are still in the process of being developed (Ankiewicz, de Swardt & Engelbrecht, 2007; Mapotse, 2015; Rauscher, 2009). The result until now has been a relatively limited philosophical, theoretical and pedagogical basis for developing teacher training programmes based on empirical research in TE. Therefore, TE research currently relies on professional models of design cognition for developing design-based curricula.

### **1.2.1 International curriculum delivery**

One of the main areas of international curriculum reformation in TE involves the modification of vocationally focused curricula. This would emphasise critical and creative higher-order thinking skills instead of manual labour skills (DoBE, 2011; Johnson & Daugherty, 2008; Walmsley, 2009). Internationally, the foundation of TE comprised craft-based, technical, and vocational subjects, which are referred to as the industrial arts (Eggleston, 2001a). The implication for South Africa was that vocational subjects such as woodwork, metalwork, needlework, and home economics served as the forerunners for technology (Ankiewicz et al., 2007; Mapotse, 2015; Stevens, 2005). As a result, emphasis was placed on manual skills training, which neglect the higher-order problem solving skills needed for designing artefacts that could address human needs and wants (Haupt, 2011; Mapotse, 2015). For this reason, during the past two decades, the transition from industrial arts to technology has brought about a reconceptualisation of technology's delivery mechanisms and curricula as this focuses more on the development of learners' cognitive abilities, rather than manual labour skills (Walmsley, 2009). Currently, numerous educational policy documents emphasise the development of design problem solving skills at the heart of TE (DfEE/QCA, 1999; DoBE, 2011; Ministry of Education, 2009). However, there still seems to be a general lack of a unified view of what design problem solving in a TE context entails (Barak, 2010; Edwards-Leis, 2007; Welch, Barlex, & Lim, 2000). Additionally, the diverse and limiting nature of the definitions of the notion of 'problems' tends to result in a neglect of the ill-structured nature of design problems and its effect on the cognitive processes involved in the design process (Haupt, 2014).

Owing to the recent focus on cognitive abilities in TE, it seems that little research in novice design behaviour is currently being reported on (Haupt, 2014; Middleton, 2010; Zuga, 2004). A review of empirical research on cognition in TE reveals that the benefits of design problem solving as a pedagogical approach still need to be evidenced. Zuga (2004) warns that:

*Yet to be determined and supported by research evidence are the following: technological literacy, problem solving as the technological method, technology as a discipline, and other "truths" that seem to be held by the technology education community. Still technology educators carry on with recommendations that would make one think that technological literacy, problem solving as the technological method, and technology as a discipline are universally accepted concepts outside of the field of technology education with research backing (pp. 2-3).*

The above excerpt suggests that design problem solving tends to be promoted without being adequately supported by empirical evidence. Furthermore, it seems to suggest that design problem solving is an unspecialised instructional approach. These suggestions seem to follow as a result of empirical studies on cognition, which are often conducted in the absence of sound theoretical underpinnings (Zuga, 2004). Given that learning theories underpin design problem solving as an effective instructional approach (Petrina, 2010), the seemingly limited use of these theoretical foundations in empirical studies leads to superficial learning theories.

## **1.2.2 South African curriculum delivery**

From a South African perspective, I have identified two spheres in which design problem solving as an instructional approach is challenged; these are in the spheres of teacher training and curriculum implementation.

Technology was introduced in 1998 into the South African education system as a compulsory subject for the first time. Prior to this, no teacher training programmes had been developed to support this introduction (Pool, Reitsma, & Mentz, 2013). This resulted in vocationally trained teachers in subjects such as home economics, woodwork, and industrial arts taking over the role of teaching technology. This was problematic as teachers often lacked experience in design practice and an understanding of design cognition to support design learning processes (Ankiewicz et al., 2007). As such, this finding supports Zuga's (2001) concern that no specialised training is required to facilitate designing.

The limited understanding of design problem solving is further confirmed by the findings of recent studies, which show that current technology teachers have limited experience in teaching technology, ranging from four to seven years (Mapotse, 2015; Potgieter, 2004; Stevens, 2005; Williams & Gumbo, 2012).

Despite the efforts of the South African Department of Basic Education (DoBE) in hosting workshops on curriculum training for in-service technology teachers, recent studies indicate that the presenters of these workshops also lack formal training in technology themselves (Reitsma & Mentz, 2009).

### 1.2.3 The South African Technology Education Curriculum

The way in which South African learners engage in design problem solving should, however, be seen in the light of the South African Curriculum and Policy Statement (CAPS) for technology. As a school subject, technology is defined as "the use of knowledge, skills, values and resources to meet people's needs and wants by developing practical solutions to problems, taking social and environmental factors into consideration" (DoBE, 2011, p. 7).

The definition of technology follows from the two main aims, which are to develop technological literacy among South African Grade 7-9 learners, and to serve the economic purpose of training future engineers and artisans, arising from a need in the South African workforce (DoBE, 2011). In order to achieve both of these aims, the technology curriculum specifies three specific aims in which learners have to (1) develop and apply specific design skills to solve technological problems, (2) understand the concepts and knowledge used in technology and use them responsibly and purposefully, and (3) appreciate the interaction between people's values and attitudes, technology, society and the environment (DoBE, 2011). By addressing these three aims, the technology CAPS intends that learners should also develop their critical thinking skills when solving design problems (DoBE, 2011). Consequently, during designing, learners should be given the opportunity to address these three specific aims while developing critical thinking skills that are based on rich information sources. The DoBE accordingly suggests that teaching and learning should follow the design process<sup>1</sup> as a backbone methodology (DoBE, 2011, p. 12). The design process stipulated by the DoBE consists of five interrelated design skills including investigation skills, design skills, making skills, evaluation skills, and communication skills (DoBE, 2011, p. 10). These stipulated design skills should be addressed when developing design solutions (DoBE, 2011, p. 10). Although specific learning activities are specified in the technology CAPS document to develop the five design skills, it does not specify how learners should access and use information sources during their design tasks. Furthermore, few guidelines are given to indicate how engagement with these sources contributes to the development of learners' design cognition. It therefore seemed necessary to study how learners access and use information sources to structure and solve their design problems.

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<sup>1</sup> For this study, this refers to 'the' design process as the backbone methodology for teaching and learning specified in the technology CAPS, as opposed to 'a' design process as the unique cognitive processes that novice and expert designers engage in whilst solving design problems (De Vries, 2005).

### 1.3 Problem statement

The CAPS document for technology states that learning and teaching should be structured according to the design process (DoBE, 2011, p. 12). The design process, as modelled by the DoBE (2011) should promote the acquisition of, *inter alia*, investigation skills, designing skills, making skills, communication skills and evaluation skills. In order to engage and acquire these design skills, the technology CAPS document proposes that: "Learners should be exposed to a problem, need or opportunity as a starting point. They should then engage in a systematic process that allows them to develop solutions that solve problems, rectify design issues and satisfy needs" (DoBE, 2011, p. 12).

It therefore seems that the DoBE suggests that learners develop their critical and creative thinking skills by engaging in design problem solving activities. Furthermore, during the design process, learners' critical thinking skills should be stimulated in order to develop innovative solutions to design problems (DoBE, 2011, p. 8). However, during my engagement with the technology CAPS document, I found limited guidelines for technology teachers to facilitate learners' critical thinking. I further conducted a word search of the term 'critical' in the technology CAPS document and found only three instances where the notion of critical thinking was promoted, and that there were limited guidelines to address this intended learning aim. Although the technology curriculum follows a prescribed model of the design process by which teachers can facilitate learners' design skills, it does not provide the necessary guidelines for teachers to plan and facilitate learners' critical thinking skills. Given the lack of adequate guidelines in the technology CAPS document, the challenges faced in South African technology curriculum delivery still persist. These challenges include the limited experience and training of technology teachers to teach design skills.

One of the key issues that plays a deciding role in the effective facilitation of critical thinking during a design process is the number and variety of information sources available to novice designers (Goel, 1995; Haupt, 2014). Encouragement to access and use of these information sources play a crucial role in guiding learners to think critically while structuring and solving design problems. This implies that teachers need to carefully plan the introduction and use of internal sources of information such as prior knowledge and experiences, as well as external resources such as pictures, drawings, reference media, and objects in the classroom (Haupt, 2014). However, to date, I could find no empirical research studies in international or national TE literature that explain and describe how novice designers access and use information sources during their design processes. I also investigated expert design cognition studies, which also revealed a limited scope of findings (Restrepo, 2006). This seemingly limited exploration could be ascribed to the constrained frameworks that have previously been used to study the design cognition of expert and novice designers (Petrina, 2010). This also means that few theoretical frameworks that have been empirically verified exist in the literature that can inform technology educators on learners' design cognition (Haupt, 2014).

Researchers in the field of design cognition (Cross, 2011; Goel, 1995; Lawson, 2005) ascribe the complexity of design problems to their ill-structured and ill-defined nature. The implication for technology is that design tasks compel learners to engage in a process of searching for appropriate information from various sources to solve their design problems (Goel, 1995). In turn, this search process enables learners to transform their understanding of the ill-structured design problem by finding appropriate information that contributes to their understanding of the problem context, and finding fit-for-purpose solutions for it.

Failing to provide adequate instructional guidelines to address information access and use during learners' design tasks might result in learning failures. These learning failures could be characterised by common and predictable design solutions due to the lack of information rich design thinking. Learners should therefore be guided towards making informed design decisions based on appropriate contextual, theoretical, and practical information in order to avoid superficial or intuitive design solutions. It is for this reason that I deemed it important to investigate how Grade 9 learners accessed and used information sources. As a result, I aimed to provide potential instructional guidelines for technology teachers to support novice designers during problem structuring and solving.

## **1.4 Statement of purpose**

The purpose of this study was to describe how Grade 9 technology learners accessed and used information sources during the early phases of their design processes. The focus was on the internal and external sources that the learners accessed and used during their problem structuring and solving cognitive phases. The significance of this examination could contribute to practical guidelines that can support technology teachers to facilitate learners during their design problem structuring and solving activities (De Vries, 2005; Haupt, 2014; Petrina, 2010).

## **1.5 Rationale**

Several scholars (Barlex & Trebell, 2008; Kimbell & Stables, 2008; Mentzer, Huffman & Thayer, 2014) concur that design problem solving is a potentially effective instructional method in TE. Yet, there seems to be a lack of empirical evidence to support the benefits of design problem solving (Haupt, 2014; Middleton, 2010; Petrina, 2010). One of the reasons given for this lack of empirical research is the complex nature of design cognition, which still remains poorly understood (Petrina, Feng & Kim, 2008). In her review of TE research studies on cognition, Zuga (2004) encourages researchers to study cognition in TE on the basis of sound theoretical perspectives in order to provide evidence for the benefits of design problem solving as a pedagogical approach.

In the past, several design researchers have recognised the seemingly opposing theoretical frameworks through which design cognition could be conceptualised (Dorst & Dijkhuis, 1995; Petrina, 2010). Currently, design researchers are encouraging hybrid theoretical models to describe the complex nature of design cognition (Haupt, 2014; Middleton, 2010; Petrina, 2010). Some of these hybrid theoretical models incorporate theories from cognitive science, anthropology, situated cognition, and artificial intelligence (Petrina et al., 2008). Studying design cognition from various theoretical viewpoints might therefore provide a unifying description of the cognitive landscape of a technology learning environment. However, few studies in TE have attempted to empirically study novice design cognition from these hybrid theoretical viewpoints (Petrina, 2010; Petrina et al., 2008; Zuga, 2004).

This study was therefore nested in the general need for empirical research in TE in the field of cognition (Johnson & Daugherty, 2008; Walmsley, 2009; Zuga, 2004). In particular, this study sought to describe how learners might engage with information sources during their design processes. The findings of this study could therefore suggest a novel theoretical framework through which design cognition can be conceptualised, as well as practical guidelines, based on theory, to support the implementation of design education curricula.

## 1.6 Aims and objectives

The primary aim of this study was to describe the typical information access and usage behaviour of Grade 9 learners during the early phases of their design processes. In order to address this aim, I sought to collect and analyse data that might reveal, *inter alia*, (1) what information sources learners access and use during the early phases of the design process; and (2) how learners access and use internal and external information sources when structuring and solving design problems. I specifically wanted to understand how information sources transformed learners understanding of the design problem and possible solutions.

A second aim of this study was to determine an appropriate research methodology that would allow me to describe the information access and use of technology learners. The conventional methods of Think Aloud Protocol Studies (TAPS) seemed to be an appropriate methodology for revealing the cognitive processes of designers. However, I needed to adapt the conventional methods of TAPS in order to (1) study novice design cognition in their technology learning environment; and (2) investigate groups of learners.

A third aim of this study was to develop practical guidelines to support technology teachers in facilitating novice design cognition. In order to address this aim, I required an appropriate theoretical framework through which I could describe the information access and usage of technology learners during their design tasks.

Furthermore, this framework would have to allow me to empirically investigate the internal and external information sources that novice designers might access and use. I accordingly sought to develop practical guidelines that would be based on sound theoretical and empirical assumptions.

## 1.7 Research questions

In accordance with my aims and objectives, the following primary research question guided the planning and implementation of this study:

### **How do internal and external sources of information contribute to the development of Grade 9 learners' design cognition during the early phases of the design process?**

The primary research question suggests a relationship between the methodological, practical and theoretical parts of this study. In order to address my primary research question, I situated my research within a case study research design, utilising TAPS methodology. Three groups of Grade 9 participants were studied. As such, my primary research question revolves not merely around the connections between the internal and external sources of information that technology learners access and use during designing, but also around the problem structuring and solving cognitive phases inherent in the early phases of a design process. This also implied that I needed to investigate the current practice, theories and methodologies used to study novice design cognition. In order to address the primary research question, the following sub-questions were formulated:

#### **1. What information sources do learners access and use during the early phases of the design process?**

This sub-question allowed me to address the primary research question by quantitatively describing the participants' design processes. I quantitatively described the design process of each group of participants by counting occurrences of problem structuring and solving phases typically found in the early phases of design processes. Furthermore, I also counted occurrences of internal and external information access and use during each group's design processes. Finally, I was able to establish what information sources were accessed and used during each cognitive phase. This first sub-question has a theoretical focus in describing the location and transformation of information sources that technology learners access and use during the early phases of their design processes. Finding empirical evidence regarding the manner in which technology learners access and use internal and external information sources may pave the way to formulating empirically based Design Cognition theory, as well as guiding the practical application thereof in the context of technology.

## **2. How do learners access and use internal and external information sources when structuring design problems?**

This sub-question informed the primary research question with regard to the way in which the problem structuring activities of each group of participants were dependent on information in the technology learning environment. This sub-research question allowed me to qualitatively describe how each group of participants accessed and used information during problem structuring. I accordingly paid attention to the contextual sequence in which the participants accessed and used information sources to transform their understanding of the ill-structured design task. In order to study the participants' information access and use activities, I relied on their external representations to evidence their transformed understandings.

## **3. How do learners access and use internal and external information sources when solving design problems?**

This sub-question informed the primary research question with regard to the way in which the problem solving activities of each group of participants were dependent on information in the technology learning environment. This sub-research question allowed me to qualitatively describe how each group of participants accessed and used information during problem solving. I accordingly paid attention to the contextual sequence in which the participants' problem solving activities developed.

## **1.8 The conceptual framework for this study**

In this study, I related the empirical findings from professional design practice and theoretical contributions of cognitive science to TE design activities. Michaelian and Sutton (2013) assert that the philosophical debate about the problem solving appropriateness and suitability of cognitive theories has often been distanced from empirical research. I concur with this assertion on the basis of my engagement with various literature sources on design education. During my practice as a lecturer, I have observed how literature sources can be categorised as either philosophical pieces on what constitutes design cognition or pragmatic guidelines that are often distanced from empirical evidence. In addition to this, various scholars in TE have recognised this separation of cognitive theories from empirical evidence and are consequently calling for in-depth studies in learners' design cognition based on sound theoretical frameworks (Middleton, 2010; Petrina, 2010; Zuga, 2004).

In order to relate the two fields of cognitive science and empirical research from professional design practice in the technology classroom, I applied an adapted Extended Cognition framework, developed by Haupt (2013). This framework allowed me to investigate how TE learners access and use internal and external information sources to structure and solve their design problems. Essentially, the appropriateness of this framework relied on its focus on describing how expert designers access and use internal and external sources of information during their design processes.

The conceptual framework is based on four assumptions, derived from expert design practice by Haupt (2013). These assumptions are that:

1. Design problems are ill-structured and complex (see Chapter 2, Section 2.2.2).
2. Information provided in the design task is insufficient, ambiguous and vague (see Chapter 2, Section 2.4.3).
3. Designers realise that they need information in order to structure and solve the design problem (see Chapter 2, Section 2.4.4).
4. Designers have access to a variety of internal and external sources of information in order to conceptualise an artefact that is appropriate to the socio-technological needs of people specified in their given design task (see Chapter 2, Section 2.4.4).

Following the four assumptions, the Extended Cognition framework integrates the Information Processing Theory (Newell & Simon, 1972) and Embodiment Theory (Gibson, 1986) to describe the design cognition of designers. This framework is discussed in Chapter 2 (Section 2.4). I was able to implement this integrated framework in a technology learning environment with the focus on internal and external information sources, which one-sided theories of design cognition would not have allowed me to achieve (Petrina et al., 2008; Petrina, 2010; Middleton, 2010).

The value of the Information Processing Theory of problem solving was that it allowed me to systematically study the verbal protocols and external representations that learners produced from moment to moment during the execution of their design task. Embodiment Theory models of design behaviour do not allow design researchers to study the cognitive activities of designers in such a microscopic manner (Craig, 2001). Empirical observations founded in Information Processing Theory allowed me to observe and describe how learners sequentially accessed and used existing information contained in their memories, and the design task. By examining their external representations, I was able to show how internal information was processed and transformed in order to contribute to the participants' understanding. Embodiment Theory allowed me to describe how learners detected information from their learning environment by means of direct perception, and acted thereupon. I subsequently examined the contextual sequence of their cognitive actions, which revealed how they transformed their understandings of the design problem.

One limitation of this framework was that it did not specify the information seeking and searching behaviour often cited in information science literature (Ellis, 1989; Wilson, 1999). The information seeking and searching behaviours of learners may be integrated into future TE studies on cognition. A second limitation of this framework was that it only allowed me to analyse data of isolated design tasks. The reason for this is that the framework focused on the microscopic development of the participants' representations and not on a holistic design process as such.

## 1.9 Significance of the research

During my research activities in the planning and implementation phases of this study, I noticed a shortage of empirical studies based on solid theoretical foundations in the field of TE design cognition. More specifically, I found a limited number of studies that report on novice designers' design cognition in TE, especially in the South African technology context. This study might therefore draw other researchers' and educators' attention to the shortage of information in the South African design cognition field. Learning about sources of information during the early phases of the design process may therefore benefit theory, research methodology, and teaching practice.

In terms of theory, the findings of this study may add to the existing literature on design cognition in general. More specifically, I hope to develop the application of the adapted Extended Cognition Theory of Haupt (2013) in an educational setting. By describing how technology learners use internal and external sources of information, I hope to extend existing frameworks for investigating cognition in TE, since existing frameworks still lack a clear focus (Zuga, 2004) and only give one-sided accounts of cognition (Petrina, 2010; Middleton, 2010).

In terms of methodology, TAPS has been a neglected data collection method in TE (Johnson & Daugherty, 2008). Recent calls for empirical research on design cognition have criticised the use of surveys and interviews, and suggested more in-depth methodologies (Zuga, 2004). Furthermore, TAPS has been utilised over the last 40 years to study the design cognition of individual designers in laboratory settings. By conducting TAPS for this study in the participants' natural technology learning environment, and enabling participants to work in groups rather than as individuals, I may potentially contribute to innovative approaches to researching design cognition in natural learning environments.

On a practical level, I was able to provide guidelines based on how the Grade 9 technology participants engaged in their design tasks. These guidelines could potentially feed into technology teacher training courses to deliver pre-service teachers who would be able to responsibly facilitate design processes on the basis of empirical evidence.

In this way, pre-service teachers might be educated on the role of information sources and cognitive phases during learners' design processes. Additionally, these guidelines might also feed into current TE classrooms by empowering technology teachers to devise courses of action aimed at monitoring and revising current educational practices.

## 1.10 Context of the study

The research site for this study was in a low socio-economic region<sup>2</sup>. The quality of the learning resources to which learners had access was accordingly limited<sup>3</sup>. For that reason, I did not consider digital media sources for inclusion in this study. The target population considered for this study consisted of Grade 9 technology learners. When technology learners start their Grade 9 technology tuition, they have already had experience of at least six projects during their high school career.

Before participating in this study, the learners in the target population had just completed a design project focusing on mechanical systems and control. In this design project they were introduced to several mechanical systems and control concepts including hydraulics, pneumatics, pulley systems, gear systems and mechanical control systems such as cleats, ratchets and pawls (DoBE, 2011). The completed design project was sequenced over eight weeks, comprising 20 contact lessons. During the lessons in weeks 1-4, the learners engaged in enabling tasks focused on developing their conceptual knowledge of mechanical systems and control. These concepts were taught mainly from activities in a textbook with limited reference to pictorial information and physical tools and materials.

During weeks 5-8, the learners completed a design task with the aim of designing and making a 3D model of a water pump, drawing on their prior knowledge of integrated mechanical systems and previous design skills. Their technology teacher provided them with some contextual information about their design problem and instructed learners to consult other sources if they needed to. I therefore assumed that the target population for this study should have developed the necessary conceptual and procedural knowledge to participate in this study. During their design project, learning activities were also structured according to activities derived from their workbooks. No tools

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<sup>2</sup> For this study, I considered the location of the school as a low-socio economic area. This consideration was supported by Abbey (2008) and Naidoo (2011). The low-socio economic status of the area could furthermore be justified in terms of the monthly income of households, unemployment rates and food insecurity.

<sup>3</sup> For this study, limited resources refer to limited access to electronic devices such as smartphones and tablets. As such, I focused on how learners accessed and used familiar and common information sources. Furthermore, the learners in the target group did not have access to textbooks. Instead, the teacher made summaries from technology textbooks, which she then gave learners to paste into their technology workbooks. The value of selecting a low-socio economic status school for this study lies in the way I could study how participants' thoughts developed as a result of common and familiar information sources. Further studies might be conducted to investigate the effect of well-resourced schools' environments on learners' design cognition.

and materials were provided by the school to make the 3D model of the water pump, hence the learners had to source their own 'affordable and easily accessible' materials. While engaging in their design tasks, the participants had access to external information sources including a prescribed textbook, a workbook, learning and teaching support materials (LTSM) such as worksheets, posters on the walls of the class, a case study they had investigated in the classroom, and books and Internet sources found in the school's library.

## 1.11 Research methodology

For this study, I adopted a pragmatic stance in order to guide my methodological decisions (James 1907; Dewey, 1931; Pierce, 1931). This study necessitated a pragmatic stance based on the integration of post-positivist and constructivist theories of design cognition (Petrina et al., 2008). The Information Processing Theory is derived from post-positivist assumptions and the Embodiment Theory, which originates in constructivism (Goldkuhl, 2012; Petrina, 2010). The integration of the Information Processing and Embodiment theories requires different theoretical lenses through which design cognition can be conceptualised. I therefore needed a paradigm that would support the integration of the underlying assumptions of both. By approaching this study from a pragmatic stance, I was able to provide an integrative view of the participants' design cognition. This stance also enabled me to collect different data types, evidencing the internal and external sources of information. In this way, I was able to address my research question to describe how these sources contributed to the participants' design cognition. I elaborate further on my paradigmatic assumptions in Section 3.1.

In order to investigate how participants accessed and used information sources, I followed a concurrent mixed methods approach (Creswell, 2014; Teddlie & Tashakkori, 2009). The manner in which each group of participants structured and solved a given design problem allowed me to collect both qualitative and quantitative data. As I believe that designing involves complex cognitive activities, as evidenced in the multifaceted conceptual framework of this study. Therefore, collecting multiple data types seemed necessary in order to provide a comprehensive description of the participants' design cognition. To this end, I collected predominantly qualitative data, which included concurrent verbal and visual data. In support of the large amount of collected qualitative data, I also collected quantitative data, which comprised temporal data. The research approach followed for this study is explained further in Section 3.3.

I adopted a case study research design (Yin, 2014) because it allowed the study of the design cognition behaviour of each group of participants in a thorough manner. Furthermore, I also wanted to acknowledge the central role that the technology learning environment plays during participants' design processes. The research site of the case study was in a South African public secondary school, situated in a relatively low socio-economic area. I therefore needed to be aware

of the limited learning and teaching support materials (LTSM) to which the target group for this study might have been exposed. This allowed me to investigate how the participants accessed and used unsophisticated external sources of information, i.e. workbooks, 3D modelling items and pictorial information, during problem structuring and solving. The extent of these sources of information is discussed further in Chapter 3.

The school in which the research site was situated was conveniently selected based on the school's willingness to participate in the study. The sample comprised eight Grade 9 female learners and was purposefully selected by the technology teacher. The criteria for participant selection were derived from the CAPS document for technology and given to the teacher for participant selection. These criteria included participants' ability to communicate effectively, work together effectively as a group, and proficiently solve design problems (DoBE, 2011). The teacher conveniently clustered the eight participants into three groups: two groups of three participants, and one group of two participants. For this case study, the participants needed to draw on their knowledge of mechanical systems and control, as well as the design skills that they had acquired in order to address the problem in the design task. The sample selection process is elaborated in Chapter 3, Section 3.5.2.

The primary unit of analysis for this study was verbal utterances made by the participants, which were clustered into modules that I could interpret as cognitive actions. I selected groups of female participants deliberately in order to ensure verbal fluency in the participants' dialogues (Fox-Turnbull, 2013; Welch, 1999). I selected groups of participants, instead of individual learners, in order to contribute to a natural technology environment and to enhance the external validity of the data. Conventional protocol studies in design cognition were often based on the thought processes of individual designers (Ericsson & Simon, 1993). However, in order to collect verbal data that would evidence the cognitive actions of participants, I utilised a Think Aloud Protocol Study (TAPS) methodology in this study. I conducted TAPS in the participants' usual technology classroom by following its requirements (Ericsson & Simon, 1993) in order to maximise the transferability and confirmability of the study (Yin, 2014).

I was able to elicit the design cognition behaviour of each group of participants by providing them with a design task that I adapted from a prescribed textbook suggested by the DoBE (Johnstone et al., 2013). The participants did not have access to this design task prior to the study. I adapted the design task on the basis of the participants' work from the previous term, focusing on concepts of mechanical systems and control. The groups of participants were required to design a model of a lifting machine that could pick up logs from the ground and transfer them onto a transport truck. The participants were also instructed before the study to bring their workbooks to class, which contained their previous terms' work. This had the potential to stimulate idea generation and enhance their problem structuring and solving behaviour.

The design task played a central role in eliciting the participants' cognitive phases and information access and use during their design processes. I could find evidence of the participants' cognitive phases and information access and use in qualitative and quantitative data. The design processes of each group of participants were video-recorded in order to collect the contextual sequence in which cognitive actions exhibited information access and use. I collected and analysed primarily qualitative data, which included concurrent verbal and visual data. Verbal data was collected sequentially from the start of the participants' protocols, while visual data consisted of external representations that participants produced in the form of sketches, 3D models and writings. Quantitative data was collected in the form of temporal instances of cognitive phases and information access and use behaviour.

The data analysis and interpretation was guided by a multi-phase coding scheme derived from Goel (1995) and Goel, Vartanian, Bartolo, Hakim, Ferraro, Isella and Appollonioet (2013) that I applied to carefully individuated utterances that were structured into modules. The result of this analysis was a microscopic analysis of the design process of each group of participants, which revealed the cognitive phases and information access and usage behaviour of participants during their design task. The data analysis methodology is further explained in Section 3.7 of this dissertation.

## **1.12 Definition of key terms**

### **1.12.1 Accessing information**

For the purposes of this study, I refer to internal information accessing activities such as recognition and recall; and external information accessing activities such as perception.

### **1.12.2 Cognitive actions**

In this study, I agree with Extended Cognition theories that 'cognitive actions' encapsulates both internal and external processing (Clark, 2008; Rowlands, 2010). I hence do not agree with traditional theories of Information Processing, which hold that cognitive actions are located only in the mind of a learner. In my view, they extend into the body and external environment (Menary, 2010; Wilson & Clark, 2009). I also do not agree with Embodiment theories of cognition, which fail to acknowledge the role of systematic internal symbolic processing and representations, claiming that the external world holds sufficient information to deny internal representation (Rowlands, 2010; Wilson & Clark, 2009). Instead, I view cognitive actions as comprising both internal and external accessing (1.12.1) and use of (1.12.10) information activities, as described by Extended Cognition theories.

### 1.12.3 Designing

This study positions itself firmly in the notion that designing is a generic rather than a domain-specific cognitive activity (Goel, 1995; Visser, 2009). I accordingly note that there may be important similarities between the design processes of different domains and expertise levels. This argument is also supported by the incorporation of a conceptual framework that is derived from expert design cognition studies (Haupt, 2013), which can be implemented and used to describe the technology participants' design cognition.

In this study, I concur with several design cognition researchers that designing is a particular type of cognitive activity (Haupt, 2014; Newell & Simon, 1972; Visser, 2009). This characterisation of design as a particular type of cognitive activity is rooted in the specific type of problem solving that occurs during a design process, i.e. ill-structured problem solving. During ill-structured problem solving, designers are goal-driven in order to address specific design requirements, constraints, and needs or wants (Archer, 1985). The end-result of designing is a detailed specification list, plan or representation of an artefact, procedure, system or device (Archer, 1984; Brown & Chandrasekharan, 1989). The cognitive activity that corresponds to producing a detailed specification consists of a dynamic process from a vague conceptual idea to a precise and detailed implementation plan for a material artefact (Kimbell & Stables, 2008; Seitamaa-Hakkarainen, 2014; Visser, 2009).

However, it should be noted that the manufacturing process, i.e. the construction and making process, of the design specification is a different process to that of design (Visser, 2009). Other design researchers (Kimbell & Stables, 2008; Achten, Dorst, Stappers & de Vries, 2005) have frowned upon the notion of designing problem solving behaviour (Kimbell & Stables, 2008). However, by viewing designing from a cognitive viewpoint, I considered designing as a particular type of problem solving activity where designers typically move between unsatisfactory mental states of unspecified information to a satisfactory state, resulting in a design specification (Goel, 1995). Problem solving therefore occurs when designers search and transform their understanding of the design problem and solution by accessing and using information to deliver a detailed specification for manufacturing.

#### 1.12.4 Early phases of the design process

The early phases of a design process are the initial cognitive phases that designers exhibit during their design processes. The purpose of these cognitive phases is to understand the scope and the features of the ill-structured design problem and to develop design solutions (Goel, 1995; Visser, 2009; Haupt, 2013). Designers typically engage in problem structuring when they consider: the needs of the users, the intentions of the client, the availability of resources, design constraints, and requirements and limitations (Goel, 1995). Designers typically engage in problem solving when they generate possible solutions, write design specifications, clarify design ideas, sketch preliminary drawings, and evaluate existing solutions (Goel, 1995).

#### 1.12.5 Extended Cognition

Extended cognition is based on the integration of the Information Processing and Embodiment theories, and describes design cognition as both an internal and an external search process in which information is internally processed and externally detected (Haupt, 2013; Young, 2004). Internal processing is usually dependent on sequential processing where information is encoded and stored in the memory. In order to gain access to information, it has to be retrieved by recall and recognition processes (Newell & Simon, 1972). External processing is dependent on direct perception where information is detected in the physical environment (Gibson, 1969). In order to gain access to information, it has to be perceived and acted upon before cognitive processing can be revealed. I believe in the value of integrating Information Processing and Embodiment theories of cognition in order to provide a multi-dimensional description of novice designers' design cognition. By providing complementary views of internal and external cognitive processes, we may gain new insights into how novice designers access and use information during their design processes.

#### 1.12.6 Ill-structured problems

Ill-structured problems are characterised by the lack of information contained in their start and goal states (Newell & Simon, 1972). This means that the problem, the method of problem solving, and the solution itself are unknown to the problem solver. The problem solver will accordingly spend a considerable amount of time in structuring the problem in order to find missing information about the problem and to generate ways in which an appropriate solution may be generated (Ollinger & Goel, 2010). Another characteristic of ill-structured problems is that they do not have one correct solution (Jonassen, 2011a; Jonassen, 2011b; Jonassen, Strobel & Lee, 2006). Solutions are therefore judged not in terms of correctness, but in terms of appropriateness to solve a problem (Jonassen, 2000). Ill-structured problems can also be solved by employing various methods to solve the problem. Ill-structured problems can be differentiated from well-structured problems, which are characterised by having only one method of solving the problem and having one correct solution.

In design cognition it is widely considered that design problems are ill-structured problems (Visser, 2009; Cross, 2011; Lawson, 2005). Therefore, designers engage in a complex cognitive activity in which ill-specified information is sought from various sources and stakeholders in order to develop a detailed description of a design specification (Visser, 2009).

### **1.12.7 Information sources**

The information accessing activities (1.12.1) and information using activities (1.12.10) are performed using both internal and external information sources. On the one hand, internal information sources refer to learners' memory and their design tasks. On the other hand, external information sources refer to writings, pictorial information, 3D modelling materials and sketches.

### **1.12.8 Technology and designing**

From a philosophical viewpoint, the nature of technology can be conceptualised in four ways: technology as artefacts, technology as knowledge, technology as a socio-technological system and technology as processes (De Vries, 2005). Designing, making, using, managing and assessing are all regarded as technological processes (Kimbell & Stables, 2008; De Vries, 2005).

### **1.12.9 Technology and Technology Education**

On the one hand, technology refers to the South African school subject prescribed for Grade 7 to 9 learners in the General Education and Training (GET) band. In Section 1.2.3, I elaborated on the principles of technology as a school subject in South Africa. Alternatively, I refer to Technology Education (TE) as the broader philosophical framework in which technology is situated. In this way, I use TE as an umbrella term to denote a subject philosophy with its own epistemology, ontology, methodology and axiology (De Vries, 2005).

### **1.12.10 Using information**

Following the purposes of this study, I refer to internal information usage activities such as adding, evaluating, elaborating, justifying, qualifying, modifying, and proposing; and external information usage such as writing, speaking, sketching and 3D modelling.

## **1.13 Outline and organisation of this dissertation**

### ***Chapter 1: Orientation of the study***

Chapter 1 provides an overview of this study with specific reference to its background, the problem statement, the rationale and the aims and objectives I wished to address in this study. I briefly discussed the conceptual framework that was used to guide my theoretical and methodological decisions. Subsequently, I briefly reviewed my methodological decisions and defined the key terms in this study.

## **Chapter 2: The cognitive landscape of technology education**

Chapter 2 presents a background to the developing field of cognition in TE. I also discuss the theoretical foundations of this study, with specific reference to two prominent theories in the literature used to describe the design cognition of designers, i.e. Information Processing and Embodiment theories. I conclude by discussing the need for an integrative conceptual framework, namely, Extended Cognition, for studying the design cognition of novice designers.

## **Chapter 3: Research methodology**

Chapter 3 presents the methodology that I designed to elicit data, which is framed in my conceptual framework, and to address the research questions. I discuss, *inter alia*, the pragmatic assumptions on which I based this study, which necessitated a concurrent mixed methods research approach. Furthermore, I position my study in a case study research design, and justify my sampling methods. I also give a detailed account of my data collection and analysis methods, after which I discuss the quality measures I adhered to for this study. Finally, I explain the ethical considerations I took into account in order to implement this empirical study.

## **Chapter 4: Data analysis and interpretation**

In Chapter 4, I present the data analysis and interpretation of the quantitative and qualitative data I collected during the TAPS process. I structured the data analysis and interpretation according to my research questions, discussed in Section 1.7. In my quantitative analysis and interpretation, I reveal the occurrences of the cognitive phases of each group of participants, as well as the occurrences of information access and usage behaviour. I conclude my quantitative analysis by discussing what information sources each group of participants accessed and used during each of their cognitive phases. In the qualitative analysis, I emphasise how participants transformed their understanding of the ill-structured design problem and possible solutions by systematically accessing and using information sources. I discuss these transformations in terms of problem structuring and solving in order to address my second and third sub-research questions.

## **Chapter 5: Conclusion and findings**

The final chapter of this dissertation presents a summary of the key findings of my empirical investigation and the conclusions I was able to reach and ground in other viewpoints on novice design cognition. In stating the conclusions I reached in this study, I list the potential theoretical, methodological and practical contributions this study might make. I specifically emphasise the formulation of practical guidelines for technology teachers, which was one of the aims of this study. I conclude this chapter by acknowledging some of the limitations of my study and present recommendations for future research in TE.

## 1.14 Conclusion

In Chapter 1, I presented the background of the current challenges facing curriculum delivery in technology, particularly how design processes are currently facilitated in the technology classroom. Two challenges currently compromising design process facilitation were identified in the domains of teacher training and curriculum delivery. Furthermore, I explained that the research problem was based on the seemingly limited guidelines in the technology CAPS document with regard to how learners might be guided to effectively access and use various internal and external sources of information during the early phases of their design processes. In order to address the research problem, I applied a novel conceptual framework developed by Haupt (2013) in a technology learning environment to describe the extended cognition of technology learners during the early phases of the design process. The rationale for this study focused on how models explaining the design cognition of technology learners might add to the theoretical, empirical, methodological and practical foundations of technology. The stated research questions located this study in a case study, concurrent mixed methods research design. Possible contributions of this study were also discussed in terms of practical, methodological and theoretical contributions. Chapter 1 concluded with a definition of key concepts and the outline and organisation of the dissertation.

In Chapter 2, I discuss the developing field of research on cognition in TE and two of the prominent theoretical frameworks through which the design cognition of designers have been conceptualised. Afterwards, I explain and justify the implementation of the conceptual framework for this study.

# Chapter 2 : Establishing the cognitive landscape of Technology Education

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## 2.1 Chapter overview

Chapter 2 presents a review of the literature underlying the conceptual framework that I used to address the research questions posed in this study. The chapter starts by taking a look at the developing field of cognition in TE. After identifying the limitations of current frameworks for studying TE learners' design cognition, and the subsequent limited empirical evidence of TE learners' cognition, I explore two theories, namely Information Processing and Embodiment Theory, used to study the design cognition of designers. On this note, I describe the appropriateness of the integrative use of these two theoretical frameworks. Integrating these two frameworks led me to adapt an existing Extended Cognition framework, derived from empirical research conducted on expert designers. This chapter concludes with an in-depth discussion of the usability of the Extended Cognition framework for conducting an in-depth empirical investigation of the information access and use of Grade 9 technology learners.

The purpose of this literature review was three-fold: Firstly, to describe previous studies conducted on cognition in TE. Secondly, to determine the opportunities and limitations of current theoretical frameworks for empirically studying the design cognition of technology learners. Thirdly, to justify my decision for adapting and using an Extended Cognition approach to studying how technology learners access and use information sources during the early phases of their design processes.

## 2.2 Research in TE on cognition

In comparison with well-established school subjects such as mathematics and science, few studies in TE have empirically investigated the cognitive nature of secondary TE learners' design processes at both a theoretical and empirical level (Petrina et al., 2008). Several TE scholars (Mc Cormick, 2004; Middleton, 2010; Petrina, 2010) have highlighted the absence of in-depth empirical studies in learners' design cognition. This shortage of in-depth investigations is the result of multiple challenges, including the infancy of TE as a school subject (De Vries, 2012), the lack of a unified view of design problem solving (Barak, 2010; Edwards-Leis, 2007; Welch et al., 2000), the lack of rigour in research methodologies employed to study cognition in TE (Zuga, 2004), and the complex nature of design cognition itself (Kangas, Seitamaa-Hakkarainen, & Hakkarainen, 2013; Kimbell & Stables, 2008). Nevertheless, general approaches to studying the design cognition of TE learners have been established in the TE literature. These general approaches investigate and report on, *inter alia*, the effects of 3D modelling on cognition (Khunyakari, Mehrotra, Chunawala & Natarajan, 2007; Mentzer

et al., 2014), collaborative cognition (Ke & Im, 2013), and gender differences in cognition (Hong, Yu & Chen, 2011). However, I found limited empirical research in the TE literature that was able to pinpoint the theoretical foundations involved in modelling internal and external information access and use by TE learners. This lack of research has also been echoed in professional design literature (Restrepo, 2006).

In the following section (2.2), I outline the development of research on cognition in TE and subsequently report on current challenges found in available theoretical frameworks to describe the information access and use of TE learners during the early phases of the design process.

### **2.2.1 Development of research on cognition in TE**

During the 1960s and 70s, while educational researchers in science and mathematics education focused their efforts on understanding problem solving, TE researchers focused on understanding the design capability exhibited by learners (Kimbell & Stables, 2008; Petrina, 2010). This period was marked by educational researchers' attempts to map and delineate cognitive processes in learners' design activities (Cajas, 2002). One of the first studies in cognition in TE was conducted by Halfin (1973), who investigated the writings of ten famous designers such as Thomas Edison and Frank Lloyd Wright, after which he employed a Delphi Technique to identify 17 mental processes that are universal in any design activity. These mental processes were claimed by Halfin to help technologists to accumulate knowledge and solve technological problems. The framework developed by Halfin was later developed (Hill, 1997; Wicklein & Rojewski, 1997) and used by other researchers (Kelley, Capobianco & Kaluf, 2014; Kelley, 2008) to identify the mental processes of learners engaged in design problem solving. Although the findings of these studies are valuable, since they reveal the internal strategies used by TE learners, they do not report on the role of the external environment as contributing to design cognition. These studies also focused on individual learners' responses and not on the collaborative design activity of learners.

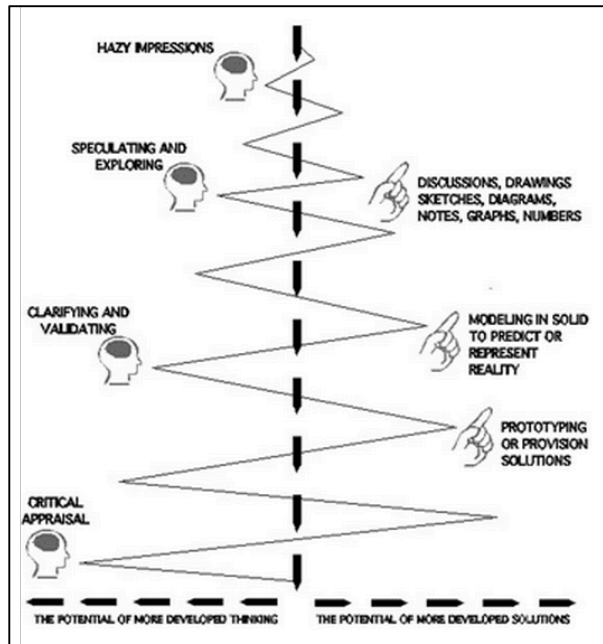
Several other TE scholars (Lemons et al., 2010; Middleton, 2005; Schunn & Silk, 2011) have advocated the need to incorporate theories of Information Processing into classrooms, especially where design activity is concerned. The reasons provided for this incorporation are based on the generalisability, transferability and replication value that Information Processing Theory provides (Blessing & Chakrabarti, 2009).

During the mid- to late 1980s, TE researchers started to include learner intentions and behaviour as units of analysis. Studies conducted under the direction of Richard Kimbell investigated learners' thought-in-action behaviour. Several large-scale studies were conducted (Kimbell, Stables & Green, 1996; Kimbell, Stables, Wheeler, Wosniak & Kelly, 1991) in order to understand the process of learning during designing. The findings of these studies revealed that design capability was both active and reflective (Kimbell & Stables, 2008) and laid the foundation for studying design activity as an

intentional activity driven by thought in action, and not as thought or activity in isolation. Questions such as what learners know and learn, and how they come to know and learn have guided research on cognition in TE ever since (Petrina, 2010). One limitation of these large-scale studies, however, was that they did not reveal the microscopic development of thoughts during the design process.

During the 1990s, Situated Cognition theories were integrated into research on cognition in TE, and have since dominated the empirical research field on cognition in TE (Jones, Buntting & De Vries, 2013). One of the main proponents of the situated cognition approach in TE education, Sarah Hennesy (1993, p. 15) argues that learning in the TE classroom “is most successful when embedded in authentic and meaningful activity, making deliberate use of the physical and social context”. Such a view of cognition is embedded in the premise that the individual and the collective group shape each other, while taking into consideration that individual interests, knowledge and skills of both teacher and learners, as well as the physical resources present in the learning environment, contribute to cognition (Jones et al., 2013). Furthermore, Situated Cognition theories also allowed researchers to investigate the complex multidimensional interactions between learners, ideas, tools and settings over time (Jones et al., 2013). However, one limitation of relating Situated Cognition theories to learning situations is the problem of knowledge transfer from one problem solving context to another (Roden, 2000). Researchers in TE have moved away from the idea that designing consists of simplistic transferable design skills and strategies (Kimbell & Stables, 2008). There is hence a need for Design Cognition theories to consider how design behaviour can be predicted in order to improve design learning situations, and in particular how information access and use during the early phases of the design process can be facilitated by teachers.

Several other TE researchers (Achten, Dorst, Stappers & de Vries, 2005; Kangas, Seitamaa-Hakkarainen & Hakkarainen, 2013; Seitamaa-Hakkarainen, Kangas, Raunio & Hakkarainen, 2012), have advocated the link between conceptual and perceptual interaction within a TE learning environment. They further explain that design activity is rooted in learners' ability to link conceptual thought with materiality and vice versa. Linking conceptual thought with materiality occurs during an iterative process between thought and action. An earlier model of the interaction between mind and hand was developed by Kimbell et al. (1991), which marked the start of conceptualising TE behaviour as linking conceptual and perceptual interaction in the TE learning environment. This model, which is depicted in Figure 2.1 and describes the interaction between thought and action, resonates well with Extended Cognition theories since it is able to describe the development of design cognition as governed by internal and external sources of information.



**Figure 2.1: The APU design and technology model (Kimbell et al., 1991)**

Although this model of designing was of significant value during the early research periods in TE literature (Kimbell and Stables, 2008), it did not allow me to describe technology learners' microscopic information access and use during the early phases of the design process. The value of this model seems to rest in its ability to describe the totality of learners' design processes, but not on an in-depth investigation of the early phases of the design process, which was the focus of this study. Another strength of this model is that it gives researchers the opportunity to account for several sub-processes during design, e.g. making judgements, solving problems, searching for information and articulating the form of ideas. However, for this study I needed a model that would allow me to identify instances of information access, use and transformation during the early phases of the design process. More specifically, I needed a model that would allow me to systematically trace how technology learners accessed and used internal and external sources of information during problem structuring and solving activities.

More recently, researchers (Kangas et al., 2013; Seitamaa-Hakkarainen et al., 2012) in TE have acknowledged Embodiment theories as a means to describe the design cognition behaviour of TE learners. Kangas et al. (2013) maintain that if teachers do not have a deep understanding of the embodied nature of designing, they might not be able to adequately facilitate design learning. This view, held by Kangas et al. (2013), is partially based on the way teachers provide material scaffolding during the design process to transform ill-structured design tasks and build knowledge for future use. The findings reveal that TE learners use material scaffolding to validate conceptual knowledge during a design process (Kangas et al., 2013). However, using Embodiment theories to describe design cognition neglects the role of internal cognitive processing.

The following statement by Norman (1993, p. 3) provides a detailed rationale for studying design cognition from within the bounds of a learners' mind:

*All the action is inside the head, yielding a natural distinction between the stuff out there and the processes taking place inside here. What could be more natural than to study the human by recognizing that the brain is the computational engine of thought, and thereby concentrating one's efforts upon understanding brain mechanisms and mental representations? Seems pretty obvious? Sure, there is a lot of action in the world at large and within sociocultural groups, but cognitive processing occurs within the heads of individuals. So, all we have to do is understand the internal mental processes and the nature of the input/output transformations of individuals, and we will have covered everything that matters.*

This statement, together with the limitations of Embodiment Theory, provide the rationale for including the Information Processing Theory of design problem solving in this study. However, I believe that the Information Processing Theory does not explain design behaviour sufficiently, since it fails to show the role of external sources of information during learners' design thinking process. Integrating the Embodiment Theory with the Information Processing Theory may provide a fruitful framework to investigate the design cognition of technology learners during the early phases of the design process (Haupt, 2014).

### **2.2.2 Designing as problem solving**

Designing is widely recognised as ill-structured problem solving (Blessing & Chakrabarti, 2009; Cross, 2011). Design problems have their own unique nature, both in practice and in technology classrooms. Brown and Chandrasekharan (1989) explain that design problems may vary on a continuum from being well-structured to ill-structured. When the goals for a design task are ill-structured, design problems are primarily open-ended and non-routine, and have no predetermined sequence of actions that are prescribed to solve the problem. Cross (2008, pp. 14-15) lists the following characteristics of ill-structured design problems:

- There is no definite problem formulation.
- Any problem formulation may embody inconsistencies.
- Formulation of the problem is solution-dependent.
- Proposing solutions is a means of understanding the problem.
- There is no definitive solution to the problem.

From these characteristics, it is apparent that ill-structured design problems can be differentiated from routine or well-structured problems. Therefore, the way in which learning in technology is facilitated should be differentiated from common problem solving teaching methods used in science and mathematics.

Some TE scholars have criticised the view that designing is problem solving (Kimbell & Stables, 2008). These arguments are the result of seeing design problems as a difficulty or a deficiency (Visser, 2004). In this view, the idea of designing as problem solving has been associated with a process where one solution is sought to end the process once and for all (Visser, 2004). Instead, in this dissertation, I adopt the view that problem solving occurs when “a person is confronted with a problem when he wants something and does not know immediately what series of actions he can perform to get it” (Newell and Simon, 1972, p. 72). The problem solving process, and subsequent designing, is however directly dependent on the nature of the problem encountered by the problem solver (Newell & Simon, 1972). In the design cognition literature, two problem types that have been identified include well-structured and ill-structured problems (Goel, 1995; Haupt, 2013; Blessing & Chakrabarti, 2008).

#### **a) *Well-structured problem solving***

Well-structured problems are characterised as problems requiring one correct solution in order to be solved. Examples of well-structured problems, for example, routine algebra and physics problems, are presented in most science- and mathematics-related textbooks. In order to solve well-structured problems, the problem solver usually requires relatively little information, such as a rule or algorithm to be applied (Newell and Simon, 1972). As such, a well-structured problem consists of a well-defined initial state, a known goal state, and a set of known constraints (Goel, 1995).

#### **b) *Ill-structured problem solving***

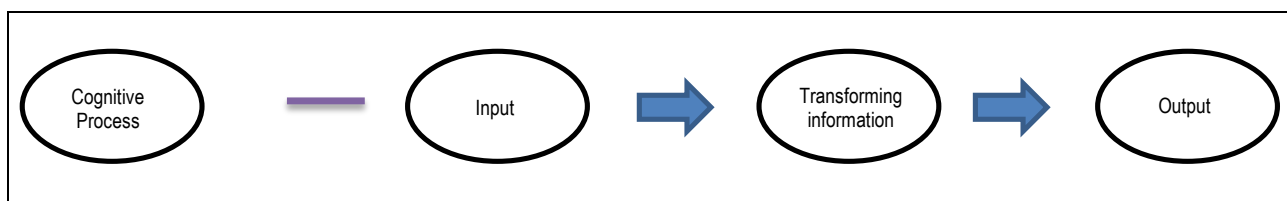
Alternatively, ill-structured problems are encountered during everyday life or professional practice, and require much more information in order to understand and solve the problem. In addition to this, ill-structured problems have a completely unspecified goal state and can have multiple solutions (Newell & Simon, 1972). Ill-structured problems also have an unspecified initial state, which requires the problem solver to search for information in order to understand the problem to be solved. Ill-structured problems are also interdisciplinary, which means that information from various domains needs to be accessed and used in order to understand and solve a problem (Newell & Simon, 1972). In order to solve the problem, the problem solver needs to find information in order to determine an appropriate methodology to address the problem (Newell & Simon, 1972).

## **2.3 Theoretical Framework**

In the following section (2.3), I outline the theoretical foundations of the conceptual framework for this study. The theoretical framework for this study is rooted in two prominent theories that describe the design cognition of designers, namely, the Information Processing Theory and the Embodiment Theory.

### 2.3.1 Information processing in a design context

The Information Processing Theory of problem solving has led to the belief that problem solving behaviour is dependent on a centralised internal processor of information located in the problem solver's mind (Newell & Simon, 1972; Goel, 1995). In this view, information is processed on the basis of the mind's rational, systematic and linear planning ability (Miller, Galanter & Pribram, 1960). The view that mental processes are obscure and residing within the minds of people complicates empirical studies of cognitive processing. In spite of this challenge, and in terms of accessing learners' internal cognitive processes, the Information Processing Theory affords an appropriate theoretical framework for modelling the internal cognitive processes of technology learners during design problem solving (Schunn & Silk, 2011). The descriptive power of the Information Processing Theory lies in the assumption that design problem solving is dependent on the input of information sources regarding a problem situation, which are systematically transformed during a design process into an output design specification (Newell & Simon, 1972), as depicted in Figure 2.2.



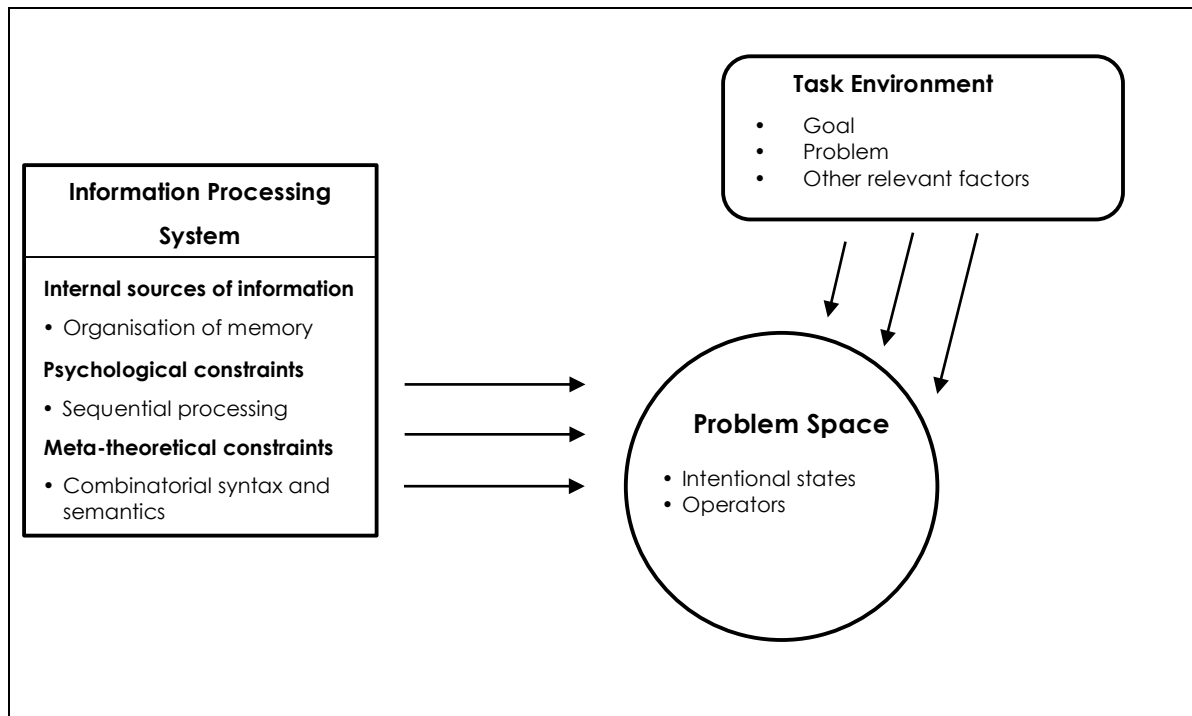
**Figure 2.2: Design cognition as information processing (Newell & Simon, 1972)**

Adopting the assumption that design problem solving is an information processing activity (Newell & Simon, 1972) allowed me to investigate the internal sources of information that systematically contributed to the design cognition of the participants during a design task. Newell and Simon's (1972) The Information Processing Theory provided me with three theoretical constructs to investigate the internal information access and use of Grade 9 learners during the early phases of the design process: an information processing system, the task environment, and the problem solving space (Goel, 1995; Haupt, 2013). In their empirical investigation of expert designers, Goel and Pirolli (1992) regarded the information processing system as a cognitive agent with a problem. Furthermore, the cognitive agent's problem solving behaviour is governed by psychological constraints, i.e. working memory limitations and sequential processing; and meta-theoretical constraints, i.e. symbol structure sensitivity and combinatorial syntax and semantics (Goel, 1995). For this study, I regarded the information processing system as the participants that executed the design task given to them. However, I did not aim to explain how the information processing system was governed by psychological and meta-theoretical constraints, as this was beyond the scope of my study.

The task environment is described as the problem, as well as the external, environment in which the information processor solves the problem (Goel, 1995). Goel and Pirolli (1992) argue that there are twelve invariant features of design task environments. For the purposes of this study, I selected two, namely, the availability of information and input/output. Selecting these two features allowed me to investigate how internal and external sources of information contributed to the design cognition of the participants during the early phases of the design process. I was able to model the information access and use by referring to the systematic incorporation of the available information that was present in the design task environment. This was done by studying the external representations that the participants made during their design processes.

The problem solving space is the modelling space that cognitive scientists use to demarcate the interaction between the information processing system and the task environment (Goel, 1995). Originally, Goel and Pirolli (1992) defined the problem solving space by including mental states, operators, evaluation functions, and control strategies in order to delineate the problem space. However, for the purposes of this study, I limited my investigation to the mental states and operators applied during design problem solving, owing to the complexity involved in empirical investigations. Furthermore, Goel and Pirolli (1992) have identified twelve invariant features of design problem solving spaces. For the purposes of this study, I focused on the distinct cognitive phases inherent in the design problem solving space (Goel, 1995). By focusing on these phases, I was able to consider the problem structuring and solving activities of Grade 9 participants during the early phases of their design processes.

The adapted framework of Goel and Pirolli's Information Processing Theory that I used is depicted in Figure 2.3 and will be discussed in the following sections.



**Figure 2.3: Components of the Information Processing Theory framework adapted from Goel (1995)**

**a) The information processing system**

The advent of computers catalysed the development of Artificial Intelligence (AI), which in turn contributed to the notion of mental processes as internal symbol processing (Barker, van Schaik & Hudson, 1998; Brooks, 1999; Wilson & Clark, 2009). The metaphor of a computer was used firstly to describe the mind of a problem solver as a processor that receives input information from perceptual abilities, retrieves information from stored memory, and performs certain operations on the input information by means of algorithms in order to transmit output information in the form of physical actions (Ritchie, 2009). Secondly, the term 'computer' was used to explain human cognitive behaviour in terms of the different cognitive stages in which information processing takes place (Gagne, Yekovich & Yekovich, 1993; Purpura, 1999). The characterisation of human cognition as an internal symbol processor resulted in the Information Processing Theory of problem solving. The aim of the Information Processing Theory is to depict human problem solving behaviour in a step-wise, linear, rational and systematic manner in order to understand, duplicate and predict future problem solving behaviour (Blessing & Chakrabarti, 2009).

The main assumption derived from Newell and Simon's (1972) theory of Information Processing is that the information processor performs basic operations, such as reading, writing, evaluating, justifying, comparing and modifying symbols that are stored in the memory of the information processor in a serial manner. The Long-Term Memory (LTM), situated in the information processing system, is

unlimited in its capacity to store information; however, information is stored relatively slowly in the LTM in a process called consolidation. Consolidation is enhanced when learners regularly revisit, understand and reapply knowledge. The LTM stores experiences, conceptual knowledge, and procedural knowledge. From an Information Processing viewpoint, design learning takes place when learners are able to consolidate knowledge, values and skills in the LTM, and are able to recall such knowledge and skills during design activities.

For the purposes of this study, I did not consider the limitations of working memory during the problem structuring and solving phases of the design process. Instead, I only considered the mental structures that gave rise to the verbal reports provided by learners during the design process. When integrating the Embodiment Theory from ecological psychology, I was also able to study how learners used sketches and writings as extended external memory devices to prevent the loss of information during designing. The Information Processing Theory did not, however, allow me to view external representations as extensions of the learners' memory.

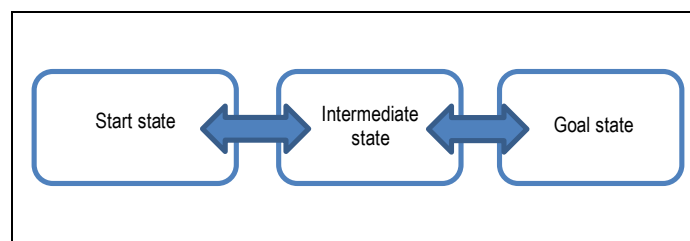
The Information Processing Theory of problem solving, which was developed by Newell and Simon (1972), seemed appropriate for investigating the internal information access and usage of Grade 9 participants for three reasons. Firstly, the Information Processing Theory allowed me to infer access and use of internal sources of information as input, transformation, and output; mental operations as transformational actions; and cognitive phases underlying information searching behaviour from concurrent verbal protocols. Secondly, although there are a number of problem solving theories, few of these theories have been extended or adapted to address the requirements of ill-structured and ill-defined design problems (Smy, 2013). Thirdly, designing is clearly a complex cognitive activity; approaching this complex activity from an information processing viewpoint gave me the opportunity to approach the access and use of internal sources of information from a systemic perspective. Hence, the Information Processing model of Newell and Simon (1972) provided me with the opportunity to model the internal cognitive processes of technology learners during the early phases of the design process as a cognitive system.

### **b) *The design problem solving space***

Design problem solving has been characterised as a searching process within a problem solving space (Newell & Simon, 1972). Several components, i.e. intentional states, operators, evaluation functions, control strategies, weak methods and problem-specific heuristics have been described to facilitate the searching process for solutions to design problems in expert design studies (Goel, 1995; Haupt, 2013). However, for the purposes of this study, I only considered intentional states and operators as facilitators of the process of searching for solutions to design problems in novice design behaviour.

In order to understand the role of intentional states during designing, it is necessary to describe the role of intentionality during the design activity. The Latin etymology of the term 'intentionality' refers to being directed towards a certain target (Jacob, 2010). A general assumption in the literature is that all human activity beyond the simplest reflexes or biological reactions is a manifestation of intentions (Kulikowich & Alexander, 2010). Intentionality can be characterised as an internal, on-going process (Juarrero, 2002), and is an invariant feature of mental states such as perceiving, remembering, believing, desiring, hoping, knowing, intending, understanding, feeling and experiencing. These mental states can be directed at an inestimable number of propositional contents or meanings. In other words, intentional states are mental states that contain intrinsic content and meaning. It is the combination of mental states and content that is causally connected in the explanation of learners' design behaviour (Dawson, 2013; Kulikowich & Alexander, 2010). This means that during designing, intentionality refers to why learners decide to engage in certain thinking and doing activities and not others. In the technology learning environment, learners have an opportunity to explore the context, situation or circumstances of a design task in which they can identify their own purpose and intentions, albeit the intentions of the teacher for learning purposes. Learners should then be able to engage in cognitive processes in order to develop design ideas that are driven by these design intentions (Kimbell & Stables, 2008).

For the purposes of this study, I considered intentionality as the design objectives stipulated in the design task, for example, safety of machinery and making work faster. I also considered it as the learners' purpose for completing the design activity in light of the constraints imposed on them in the design task and learning environment (Griswold, 1987). This implied that I regarded the different mental states of the learners as attempting to understand and align their intentions to those of the design task. One important methodological decision that I made was to consider a group of learners sharing the same intention as the unit of analysis. Thus, my focus was not on individuating collaborative cognition.



**Figure 2.4: Intentional states contained in the problem solving space (Goel, 1995)**

Figure 2.4 depicts the intentional states present in the problem solving space that guide the search for a solution to a design problem (Newell & Simon, 1972). The first intentional state in the problem solving space is the start state, which contains all the information that is known about the problem at the start of the problem solving activity. However, ill-structured problems are characterised by their

lack of sufficient information in the start state (Newell & Simon, 1972; Goel & Pirolli, 1992). In other words, the start state can be identified when learners receive the design task for the first time and realise that they need additional information in order to solve the design problem.

The second intentional state contained in the problem solving space is the goal state, which is ill-defined (Newell & Simon, 1972; Goel & Pirolli, 1992). The goal state represents multiple solutions that could address the ill-structured problem in the start state. The nature of the ill-defined goal state suggests that there is insufficient information to solve the problem and that there might be multiple solutions to satisfy the problem. As such, when learners receive the design task, they have to engage in a process of accessing and using suitable information to specify a final solution which might address the design problem.

In the problem solving space, the problem solver applies a set of mental operators in order to move from the start state to the goal state. When dealing with design problem solving spaces, more than one operator is required to transform the start state into the goal state; therefore several intermediate states may emerge during the problem solving process (Newell & Simon, 1972; Goel, 1995). As such, when design problem solving is dealt with in the technology classroom, operators denote the internal cognitive strategies that learners draw on to find or generate new information. For example, during a design task, learners might evaluate new information about the problem context in order to determine its relevance and usefulness so as to understand the design problem. The extent of such mental operations might include recalling, recognising, elaborating, evaluating, modifying, qualifying or proposing (Goel & Pirolli, 1992). For this study, I relied on the external representations that the participants made in order to evidence instances of mental operations (see Chapter 3, Section 3.7).

The sum of the intermediate states that is created by the application of operators results in the search space (Newell & Simon, 1972; Goel & Pirolli, 1992). The search space is created when the problem solver applies several operators to find and generate information during design problem solving. Therefore, the search space models all the information sources that were accessed and used during the design process, which are contained in the memory of the problem solver (Middleton, 2005). The search space also suggests that learners' understanding of the design problem and its solutions are transformed, since relevant and useful information is gained and created (Kangas et al., 2013).

The implication of using the problem solving space model for describing the design cognition of technology learners is that it provides a systematic, linear and regimented framework for tracing how learners access and use internal sources of information to solve design problems (Goel & Pirolli, 1992; Haupt, 2014; Middleton, 2005). However, problem solving space models do not consider the overt behaviour of designers as contributing to design cognition (Haupt, 2013). Therefore, designing

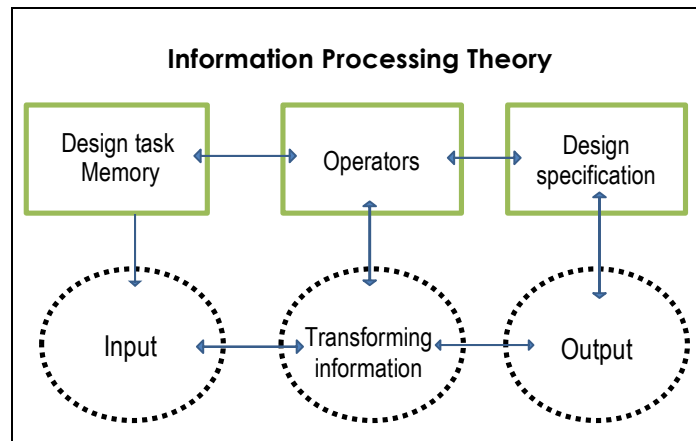
is only viewed as an internal cognitive process located in the mind of the designer. As such, the problem solving space model only allows researchers to model the internal cognitive strategies and internal sources accessed and used during design problem solving, and not how designers access and use external sources of information. The implication for design research is a one-sided view of design cognition, which neglects the role of the physical and social environment in which designers solve design problems (Shani, 2013), specifically how direct perception contributes information to the ill-structured problem solving space of designers (Haupt, 2013). One way of studying how designers access and use external sources of information in their physical environment may be through an integration of the Embodiment Theory. This integration is discussed in Section 2.4.4.

### **c) *The design task environment***

The design task environment is a theoretical construct used by cognitive scientists to denote the problem, goal and other external factors relevant to the problem solving activity (Newell & Simon, 1972). Goel and Pirolli (1992) further argue that design task environments exhibit twelve common features in design problem solving situations. With regard to this study, I specifically focused on the first and seventh common features, namely, the availability of internal information during design problem solving; and the notion that design problem solving activities start with input information about a problem and end with an output design specification (Goel & Pirolli, 1992). By focusing on these two common features, I was able to study which sources of information were accessed and used during a design task, as well as how these sources of information were used to transform the ill-structured problem space. These transformations are the outcome of operators being applied to informational content, as discussed in the previous section.

When dealing with design problems, it is generally acknowledged by scholars in design cognition (Lawson, 2005; Cross, 2011; Blessing & Chakrabati, 2009) that designers initially lack sufficient information to structure and solve design problems. Information about the design problem itself, the design goal in addressing the problem, and allowable actions that could be taken by designers to solve the problem are initially vaguely specified (Goel & Pirolli, 1992). During the early phases of design processes, available internal information sources are accessed and used to structure and solve design problems (Visser, 2009; Goel, 1995; Haupt, 2013). Design task environments in the early phases of the design process are therefore characterised by a general lack of internal information sources, which compels designers to engage in information access and use activities. I accordingly gave the participants in this study an open-ended and ill-structured design task, which required them to engage in information access and usage activities in order to find appropriate information to address the design task. The role of the design task is addressed in Chapter 3, Section 3.7.2.

The notion that design problem solving activities start with input information about a problem and end with an output design specification (Goel & Pirolli, 1992) is graphically represented in Figure 2.5.



**Figure 2.5: Design problem solving activities as an input/output system**

From an information processing viewpoint (as shown in Figure 2.5), the input information that designers access and use to structure and solve design problems is typically located in the design task from the client, or in the designer's memory. Input information relates to information about the people who might use the designed artefact, the goals they want to satisfy, and the behaviour the artefact needs to exhibit in order to satisfy the design goal (Goel, 1995). The output information of a design problem solving activity is the final detailed design specification (Goel, 1995). The mental operations performed on relevant and useful information about the design artefact iteratively mediate between the input and output information (Goel, 1995). For this study, I therefore focused on how the participants were able to access and use input information that contributed to design problem structuring by asking questions about the user's needs, design objectives, and problem context. I focused on how the participants solved their design problems by asking questions about the function, behaviour and structure of the artefact. I also focused on how learners used the accessed information to solve the design problem by writing design specifications and generating physical and functional information about the design solution. Given the focus of this study, which was on the early phases of the design process, I only focused on input information. Output information could be the focus of study during the development and detail design phases (Goel, 1995).

One limitation of the design task environment that is postulated by Goel and Pirolli (1992) is that it does not describe how designers might access and use external sources of information during the early phases of the design process (Haupt, 2013). However, in their description of what constitutes the design task environment, i.e. the problem, goal and other external factors, Goel and Pirolli (1992) seem to underspecify 'other relevant factors' (Gero, 1998; Haupt, 2013). For the purposes of this study, in agreement with Haupt (2013), I considered 'other relevant factors' to include designers' ability to access and use embodied information during a design task.

To this end, I adopted the notion of 'extended design task environment', theorised by Haupt (2013), by including the Embodiment Theory to describe how the technology participants interacted with their physical environment by means of direct perception of structure and solving of their design problems. I explain the notion of 'the extended design task environment' in Section 2.4.4.

### 2.3.2 Embodiment Theory

Embodiment theories have arisen from various disciplines such as linguistics (Lakoff & Johnson, 1980), dynamic systems theory (van Gelder, 1995), developmental psychology (Thelen & Smith, 1994), cognitive science (Kirsh & Maglio, 1994), and philosophy (Clark, 2008; Wilson, 2004), to name a few. Its philosophical roots may also be traced back to the writings of Vygotsky (1978) and Gibson (1986).

Embodiment theories are based on Gibson's (1986) explanation of how vision is the result of direct perception, rather than complex information processing (Young, 2004). Embodiment theories hence rely on a view of cognition in which learners are seen as information detectors, rather than information processors (Young, 2004). Although the Information Processing approach to problem solving generally acknowledges the role of perception of the environment as stimulus input, it relies on the assumption that cognition is bound to the minds of learners, and does not account for bodily interactions with the environment (Bickhard, 2008; Ionescu & Vasc, 2014).

Recent studies from the viewpoint of Embodiment Theory, especially in the learning sciences, have shown that the problem solving behaviour of learners is dependent on the environments in which such behaviour takes place (Barab & Roth, 2006; Normak, Pata & Kaipainen, 2012). From an educational perspective, the dependency of behaviour on the physical environment has been shown to denote intentional cognition that is based on Embodiment Theory, namely, direct perception and affordances (Barab & Roth, 2006). Therefore, when developing teaching programmes, teachers should thoughtfully consider how the physical environment could scaffold both conceptual and perceptual understandings (Kangas et al., 2013).

The way in which designers directly perceive information from the external environment is often neglected in Information Processing accounts of problem solving (Haupt, 2014; Kirsh, 2009). It is for this reason that I decided to integrate the Embodiment Theory with the theory of Information Processing in order to understand how information from the physical environment contributes to learners' design cognition. In this section, I explain how the Embodiment Theory may contribute to a more comprehensive view of the design problem solving activity, i.e. how the extended design task environment may include both internal and external sources of information (Haupt, 2014). This implied that, for this study, I investigated the relationship between the learners' internal and external information sources that were contained in the learning environment, which they accessed and used to structure and solve design problems during the early phases of the design process.

### **a) Intentions as drivers of behaviour**

The Embodiment Theory presupposes that intentionality and personal goals are given primacy over the interaction between agent and environment (Young, 2004). When the behaviour of learners is studied, intentions are typically visible goals that have meaning or functional value for the learner (Young, 2004). Essentially, learning is viewed as the result of self-directed behaviour based on the personal goals and intentions of learners within a learning environment (Young, 2004). Yet, it must be acknowledged that how learners interact with their learning environment could produce changes in the environment, which can create or eliminate goals (Young, 2004). Therefore, when learning based on Embodiment theories is studied, information regarding the changing learner (intentional dynamics) and the changing environment should be available.

### **b) People as information detectors**

Embodiment theories argue that cognition arises from people detecting functionally defined information that is specified by the physical environment, and consequently taking action thereupon (Young, 2004). Gibson (1986) emphasises the role of direct perception in detecting information from the environment, asserting that perception could only be understood in terms of both the perceiver and the perceived. As such, he views perception as 'direct', in contrast to Information Processing theories of perception as encoded mental representations from environmental stimuli. In other words, Gibson (1986) believes that information exists in the physical environment that is directly available to the perceiver. The notion of direct perception can hence not be understood independently without reference to action. In order to describe the functional value of information in the environment, Gibson (1986) introduces the concept of 'affordances' to explain how functional information in the physical environment might provide opportunities for action. For example, doorknobs afford turning, pencils afford drawing and buttons afford pressing. For educational research on cognition, this implies that information access and use cannot be understood by studying the learners alone, but only by examining the relationship between learners and their actions in a learning environment.

For this study, I focused on how the participants visually detected information in their learning environments on which they were able to act. Gibson (1982, pp. 404-406) suggests that a perceiver detects embodied information from the following visual elements, including:

- *Shape (square, cylinder, rectangle, triangular);*
- *Form (organic, anorganic);*
- *Size (big, small, large, tiny);*
- *Colour (red, green, yellow);*
- *Texture (rough, smooth);*
- *Line (straight lines, curvy lines);*
- *Proportion (higher than, lower than, bigger than);*

- *Weight (thick, thin);*
- *Position (from here to there, to far from there);*
- *Motion (moving, downward, upward);*
- *Surface layout (slant, edges, curvature, corners, faces);*
- *Substance (solid, liquid, viscous); and*
- *Lighting (darker, lighter, dim, bright).*

I was hence able to use these visual elements to study how the participants in this study detected information from their physical environment and acted thereupon.

### **2.3.3 Embodiment in a design context**

Goel (1995) argues that the nature of the design task environment influences the way in which designers might structure and solve design problems. Drawing on the empirical study conducted by Haupt (2013), I argue that the external learning environment in which learners engage in design tasks might also influence the way in which technology learners structure and solve their design problems during the early phases of the design process. As such, direct perception and action cycles contribute toward the characterisation of the design task environment (Haupt, 2013). Empirical studies conducted on expert design cognition confirm that direct perception of the physical environment seems to influence the way in which expert designers structure and solve design problems (Gero, 1998; Schön & Wiggins, 1992; Haupt, 2014). Furthermore, scholars have also noted the role that external representations play during the early phases of the design process. Suwa and Tversky's findings (1997) have demonstrated how expert designers use their sketches to iteratively access useful information at different times during the design process. Several other studies have also investigated the role of external representations during designing (Goldschmidt, 1991; Haupt, 2013; Goel, 1995).

Embodiment theories have also been used to investigate the information usage of learners in a TE environment (Kangas et al., 2013), more specifically how information is accessed and used from physical materials and constructed external representations to scaffold the learning experiences of learners (Kangas et al., 2013; Welch, 2000). However, several TE scholars have warned against one-sided embodiment approaches as materiality is seen only as a means to an end, rather than as part of the cognitive process (Petrina, 2008; Middleton, 2010). This criticism of empirical investigations specifically implies the notion that material artefacts only mediate learning and do not form part of cognition itself, which is described in Activity Theory, and situated views of learning (Petrina, 2008). Therefore, I was determined to find an appropriate theory that could provide an integrative view of design cognition within a technology learning environment.

### 2.3.4 The need for integration of theories

Petrina (2008) acknowledges the limitations of current theoretical frameworks that are inadequate for current empirical research studies in TE literature as they are not able to account for cognition and materiality. While traditional Information Processing theories of cognition emphasise the individual mind, and under-theorise the social and material environment, the Embodiment Theory de-emphasises internal sources of information and processing (Cajas, 2002; Shaffer & Clinton, 2006). In the following section, I discuss the limitations of both the Information Processing and Embodiment theories relevant to this study.

#### **a) *Limitations of the Information Processing Theory***

The Information Processing approach to design cognition has two major limitations that led me to integrate Information Processing with Embodiment theories of design cognition. The first limitation of the Information Processing Theory involves the emphasis on the mental states of the problem solver and the exclusion of elements of human behaviour within the external problem solving environment, these being seen as contributing to cognitive activities (Haupt, 2013; Kirsh, 2009). The emphasis on the individual's mental states means that the mind is seen as the central source of information, and the role of the physical environment in which designing occurs is thus neglected (Chandrasekharan & Osbeck, 2010). Integrating the Information Processing and Embodiment theories of design cognition allowed me to view the design task and the participants' memory, as well as the physical environment of the participants as sources of information that contributed to their design cognition (Haupt, 2013).

A second limitation, which led me to integrate the Information Processing and Embodiment theories of design cognition, was the inability of the Information Processing Theory to account for the unique nature of design problems, which are ill-structured, dynamic and creative in nature, as opposed to systematic, linear and isolated from context (Dakers, 2005; Hill, 1998; Jarvinen & Twyford, 2000; McCormick, 2004).

#### **b) *Limitations of the Embodiment Theory***

One limitation of the Embodiment Theory, which led me to integrate it with Information Processing theories of design cognition, is that it rejects the value of internal representations and the systematic, moment-by-moment processing of internally stored information (Haupt, 2013, Kirsh, 2009). Embodiment theories emphasise the role of the external environment as providing sufficient information, as opposed to the computational processing of information (Kirsh, 2009). A further limitation of design cognition models that are derived from Embodiment theories is that the findings of studies cannot be generalised owing to the situated nature of the environment in which the design cognition takes place (Kirsh, 2009).

This also implies that the empirical findings derived from Embodiment studies are highly interpretative and are subject to the context of each unique study (Kirsh, 2009). As Petrina et al. (2008) state, the challenge for researchers in TE is to move toward a hybrid view of cognitive processes, including mind, body and environment, in empirical investigations. This implies that, instead of seeing Information Processing and Embodiment theories at opposite ends of a cognitive continuum, researchers should adopt an integrated approach towards investigating cognitive activities based on the integration of these two theories. In an effort to model how expert designers use internal and external sources of information, Haupt (2013) found that the Extended Cognition Theory, which is an amalgamation of the Information Processing and Embodiment theories, provides a useful framework for explaining how expert designers access and use sources of information to structure and solve design problems.

## **2.4 Conceptual Framework**

For the purposes of this study, I adapted and used the Extended Cognition framework developed by Haupt (2013) as my conceptual framework. I regarded the design task environment postulated by Goel and Pirolli (1992) as extending into the external environment, and will now refer to an extended design task environment. The extended design task environment includes internal and external information sources. The reason for including both internal and external sources of information is based on my belief that the reality of design cognition may be better understood if the Information Processing and Embodiment theories are integrated and combined. Combining these two approaches to studying design cognition allowed me to describe how learners' transformed their understanding of the design problem and solution by accessing and using internal and external information sources.

### **2.4.1 Towards an Extended Cognition framework**

The Extended Cognition Theory developed from two distinct disciplines, namely, cognitive psychology and anthropology (Rowlands, 2010; Hutchins, 2014). While cognitive psychology emphasises the role of the individual in a physical environment, as well as internal sources of information, anthropological influences enabled researchers to study cognition as interactions between individuals and their natural settings, with technical artefacts and the environment as sources of information (Wright, Fields and Harrison, 2000).

The focus of the Extended Cognition Theory is therefore on how learners might access and use internal and external information during cognitive activities. Accordingly, when using the Extended Cognition Theory, I aimed to describe learners' processes of coordinating internal and external sources of information to provide a description of a robust extended information processing system. In other words, I wanted to identify what internal and external sources of information the learners used to structure and solve design problems, as well as how they used these sources of information

to generate new information that can transform the ill-structured nature of the design problem. For the purpose of this study, I viewed design cognition from an Extended Cognition viewpoint where learners engage in a process of integrating or exchanging information from internal and external sources of information to transform their understanding of the design problem and its possible solutions.

Extended Cognition theories depart from the position that cognition is constituted by both complementarity and parity of internal and external resources within the mind, body and environment of learners (Clark & Chalmers, 1998; Hill, 1998; Hutchins, 2014; Menary, 2007). This means that, in a learning environment, learners' internal cognitive processes are closely coupled with external resources in a two-way interaction, which implies that different and similar inner and outer elements cooperate symbiotically to create a cognitive system that might support learning (Arnau, Ayala & Sturum, 2014). Extended Cognition theories are therefore sensitive to the role that the social, cultural, and material environment plays in constituting learners' cognitive processes (Hutchins, 2014).

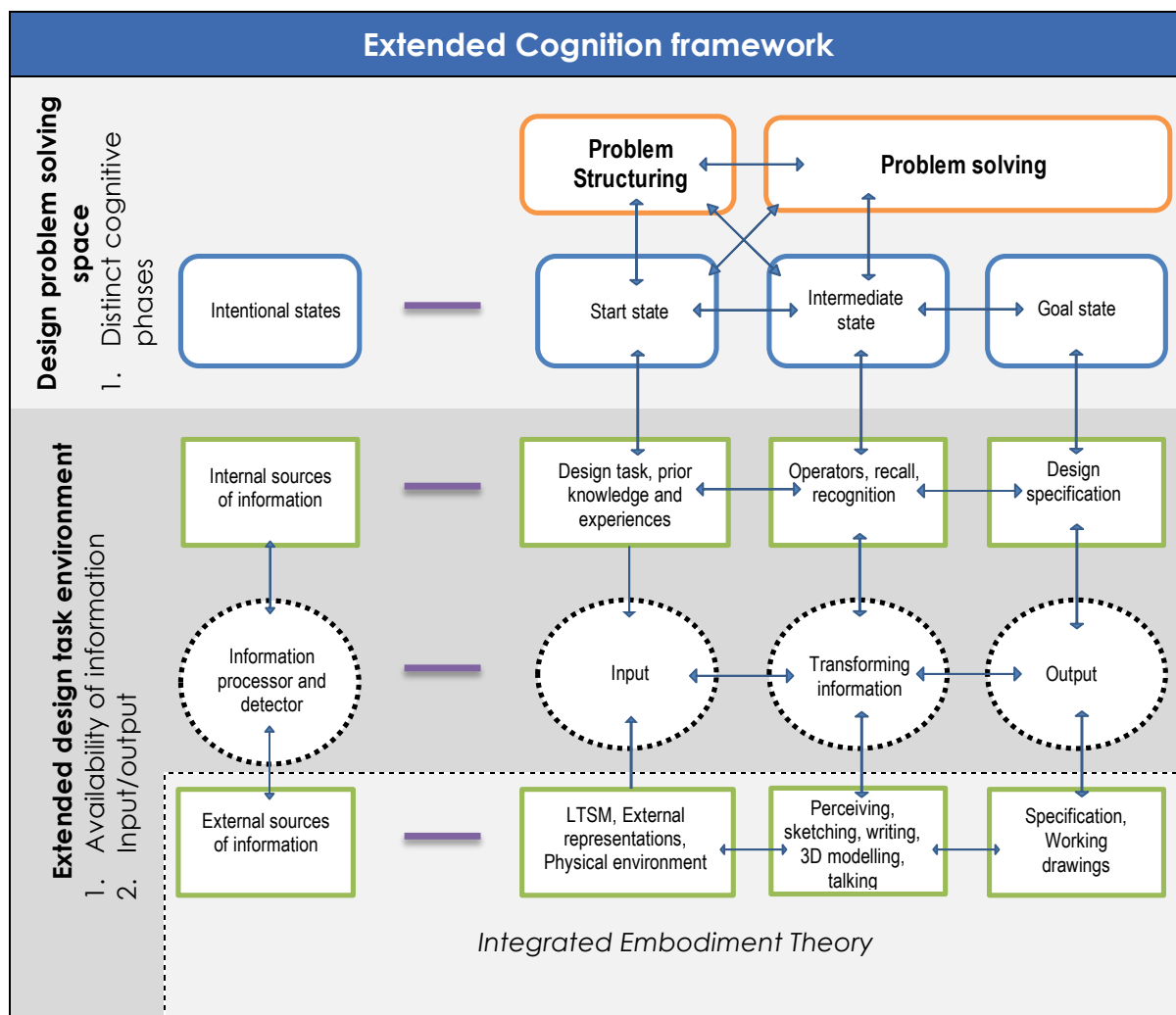
In Table 2.1 I provide a brief summary of both the Information Processing and Embodiment theories of design cognition, and give the implications for researching extended cognition.

**Table 2.1: Summary of the Information Processing and Embodiment theories and the implications for Extended Cognition**

Information Processing Theory of Designing	Embodiment Theory	Implications for Extended Cognition in technology
<b>A. The cognitive landscape in which design cognition takes place</b>		
Mind and body are separated. The mind is a centralised processing unit. Sensory information is mere input and behaviour is seen as output. The mind can be studied in isolation (Goel, 1995).	Body and environment are an integrated system of interaction and cannot be isolated from each other (Young, 2004).	Mind, body and environment are an integrated system. Interaction between body and environment feeds information into the problem space, which can be internally processed sequentially in order to structure and solve design problems (Haupt, 2013).
Design cognition is an internal searching process across mental states. These mental states lack information, as typified by ill-structured design problems. Design cognition is therefore seen as centralised processing in the minds of learners (Barab & Roth, 2006).	Design cognition is emergent based on learners' self-organising behaviour within a situated learning environment. Design cognition is also decentralised, governed by bodily interactions with external sources of information in the environment of learners (Young, 2004).	Design cognition is both an internal searching process in which mental states are accessed, as well as an emergent behavioural activity governed by interactions with the learning environment. In essence, design cognition is a process of integrating or exchanging information from internal and external sources of information to generate new information (Haupt, 2013).
Design cognition is dependent on internal processing that is rational, intentional, systematic and linear (Goel, 1995).	Design cognition is intentional and emergent; and depends on actions performed on the external environment. These actions are caused by learners' ability to self-organise elements within their learning environment (Young, 2004).	Design cognition is enabled by what learners perceive and act upon. These interactions are inputs to be internally processed in a rational, systemic and sequential process (Haupt, 2013).
Design cognition manifests itself through thinking by means of storing, recognition and recall of internally stored information (Goel, 1995; Blessing & Chakrabarti, 2009).	Design cognition manifests itself in doing and is therefore context-bound (Young, 2004).	Although design cognition is situated and dependent on context, generic cognitive phases exist based on an ill-structured problem space, extended task environments and information processors (Haupt, 2013).
<b>B. Location of information</b>		
Sources of information are internally located in the task environment and Long-Term Memory (Goel, 1995).	Sources of information are externally located based on the learners' relationship with their environment (Young, 2004).	Sources of information are located internally within the learners' minds as well as externally in physical entities and external representations (Haupt, 2013).
<b>C. Mechanisms enabling design cognition</b>		
Meaning is mediated by inferential mechanisms based on internal representations (Goel, 1995).	Meaning is mediated by perception-action cycles within the learners' environment (Young, 2004).	Meaning is mediated by computational processing as well as interaction within the learning environment. As learners interact with the environment, information is internally processed in order to transform the ill-structured problem space (Haupt, 2013).
<b>D. The nature of representations</b>		
Thinking is governed by the rule-based symbol processing reflected in internal representations (Goel, 1995).	Disregards internal representations and views the external environment as external representations used to facilitate cognition. Cognition is facilitated by learners' ability to make perceptual and conceptual connections with the external environment (Young, 2004).	Thinking is still governed by rule-based symbol processing; however, information from the external environment also feeds into the information processor by means of direct perception. This information might be perceived in order to transform the ill-structured design problem space, which is transformed (Haupt, 2013).

## 2.4.2 Elements of the conceptual framework

In the following section, I discuss the elements of an Extended Cognition conceptual framework, (Haupt, 2013), and how it was adapted to investigate the information access and use of Grade 9 technology learners during a design task.



**Figure 2.6: Adapted Extended Cognition framework for technology (Haupt, 2013)**

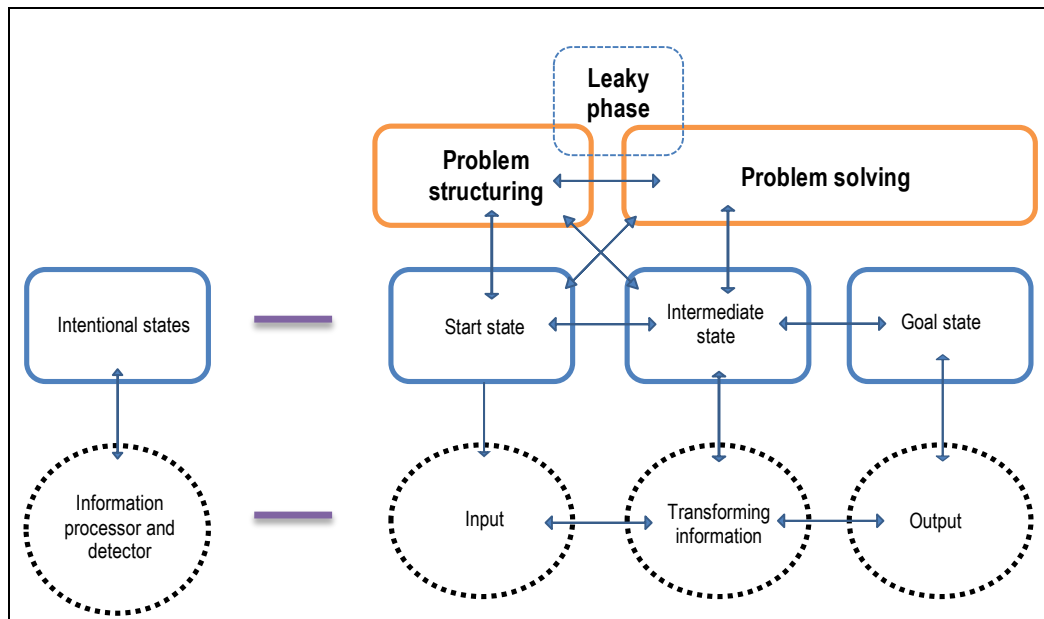
In Figure 2.6, the Extended Cognition Theory suggests that learners solve design problems in terms of an internal design problem solving space. During designing, learners access a variety of available information sources in an extended design task environment. The extended design task environment is characterised by internal and external information sources. Internal sources include information, which is found in the design task, or is stored in the learners' memory. External information sources are located externally in the technology learning environment and include sources such as sketches, workbooks, 3D modeling materials and pictorial information.

### 2.4.3 The design problem solving space

I decided to use Haupt's framework (2013), which incorporates Goel and Pirolli's (1992) framework of expert designers' design problem solving space. I adopted this conceptual framework to investigate the design problem solving spaces of novice designers. This investigation might provide fruitful results, as limited empirical research has been conducted on novice design cognition (Petrina, 2010; Zuga, 2004; Middleton, 2010).

Using the design problem solving space theory from Goel and Pirolli (1992, p. 92) allowed me to adopt the notion of generic design: "Problem spaces exhibit major invariants across design problem solving situations and major variants across design and non-design problem solving situations." Adopting the notion of generic design implied that I could use the framework derived from expert design cognition studies and implement it in the technology learning environment. In that way, I was able to study a major invariant (Goel & Pirolli, 1992) of the design problem solving space of Grade 9 technology participants in this study, namely, the distinct cognitive phases designers might exhibit during a design task. Hence, the findings of this study could contribute to my understanding of the link between novice and expert design behaviour. This implied that I would be able to identify distinct cognitive phases in novice design behaviour, which are also prevalent in expert design cognition, in order to formulate guidelines to facilitate novice design cognition. The methodological implications of studying the cognitive phases of technology participants are discussed in Chapter 3, Section 3.7.

During the early phases of the design process, which were the focus of this study, it has been found that two distinct cognitive phases exist: problem structuring and problem solving (Goel, 1995; Haupt, 2013). Goel (1995) proposes that cognitive phases imply that designers typically engage in specific activities during each cognitive phase in order to select the relevant information pertaining to specific cognitive needs during the design process. For this study, I considered the problem structuring phase as the start state in which the design task was given to the participants for the first time, and the state in which they used information sources to understand the design problem. I also considered the intermediate state as the design problem solving phase where learners transformed existing information and generated new information in order to arrive at the goal state. The relationship between the cognitive phases during the early phases of the design process, intentional states and the Information Processing Theory, is graphically represented in Figure 2.7.

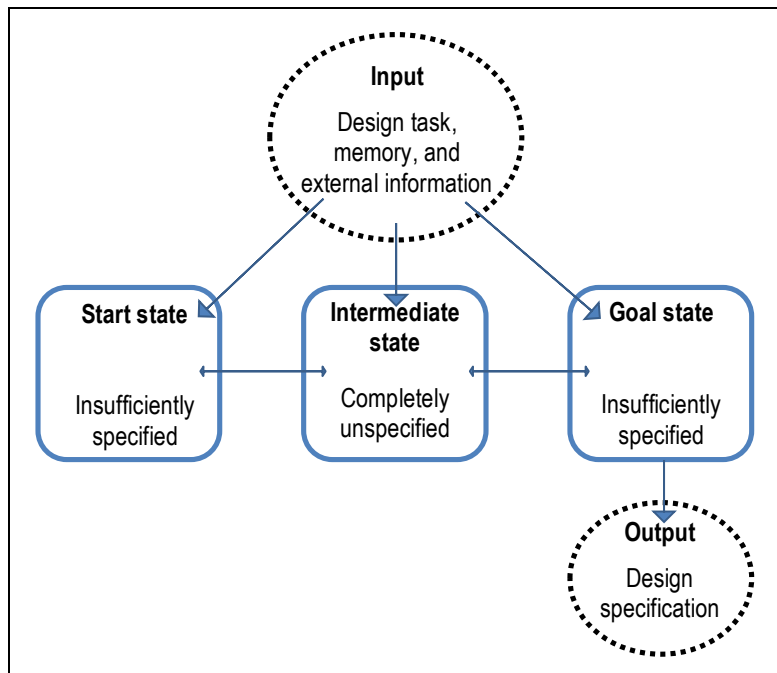


**Figure 2.7 Cognitive phases and the Information Processing Theory**

Considering the ill-structured nature of design problems, cognitive phases enable design cognition researchers to understand how information is sought and used in order to solve design problems (Goel, 1995; Haupt, 2013). This means that the information provided in a design task is insufficient for learners to determine what the design solution should be. In terms of the Information Processing Theory, this implies that information provided at the start state is insufficient to determine the goal state. Therefore, designers will typically engage in a process of understanding the design problem in order to generate new information that might lead to finding appropriate design solutions, i.e. they will engage in problem structuring<sup>4</sup>.

The lack of information in designers' three intentional states requires extensive problem structuring (Goel & Pirolli, 1992; Haupt, 2014). Design problems, characterised by their ill-structured nature, consist of ill-defined goals, states or operators (Goel & Pirolli, 1992) and therefore require access to and use of information in order to understand and solve the design problem. The scarce distribution of information is graphically shown in Figure 2.8.

<sup>4</sup> Some authors also refer to this cognitive phase as problem framing (Kirsh, 2010) or problem setting (Schön, 1983).



**Figure 2.8: Information distribution in the design problem solving space**

Learning in design is therefore facilitated by not knowing, since designers have no concrete image of the goal they might aim for in order to solve the design problem (Seitamaa-Hakkarainen, 2011). What is presented in the design task are a few constraints, objectives and a little about the path leading to the achievement of those objectives (Woelfel, Krzywinski & Drechsel, 2013). Not knowing is also linked to uncertainty and decision making (Kimbell & Stables, 2008). In technology, decisions about a design solution are concerned mainly with function and fit (DoBE, 2011); however, few guidelines are provided for technology teachers to support the systematic considerations that enable informed decision making. It has also been noted by (Woelfel, Krzywinski, & Drechsel, 2013) that novice designers feel inconvenienced when there are no objective rules for making decisions during the early phases of the design process.

By using Information Processing theories to study the design cognition of TE learners, researchers might be able to develop appropriate guidelines for TE teachers to facilitate the early phases of the design process. More specifically, Information Processing theories might highlight the importance of the instructional planning of information sources as input information to engage learners in problem structuring and problem solving activities (Haupt, 2014). Information Processing theories of design might also be able to describe how learners access and use sources of information on the basis of the systemised mental operations that they apply to accessed information. Practically, this means that learners' cognitive engagement with sources of information might be highlighted, instead of their designed artefacts at the end of each term (Eastman, 2001).

Furthermore, Information Processing theories also highlight the prominence of a well-formulated design task and design problem as input information, by which learners might be empowered to access and use relevant and sufficient information sources. Although the quality of a well-formulated design task plays a central role in the effective facilitation of technology learners' design processes (Haupt, 2011), this was not the focus of this study and can be addressed in future studies.

Design cognition literature has noted the difficulty of inferring cognitive phases from design activity owing to the natural overlap between problem structuring and solving (Goel, 1995; Restrepo & Christiaans, 2006). Taking this into account, my methodology (as discussed in Chapter 3, Section 3.7) ensured that I could identify clear instances of each cognitive phase, as well as instances where problem structuring and solving overlapped. In instances where problem structuring and solving overlapped, I referred to 'Leaky phases' (Goel, 1995; Haupt, 2013).

### **a) Problem structuring**

Problem structuring refers to the process in which designers engage in finding missing information about the problem provided in the design task (Goel, 1995; Haupt, 2013, Kirsh, 2010). This implies that when participants receive a design task, they try to understand the problem that they need to solve, what types of requirements are needed to solve the design problem, what the design constraints are, and what limitations their design process are governed by. Since this information is not included in the design task, participants typically search for information in their extended design task environment. Therefore, sources of information play an integral role during the problem structuring phase because they serve as the basis for interpreting the design task, clarifying constraints and objectives, developing concepts, and laying the foundation for designing a solution to the problem presented in the design task (Goel, 1995; Haupt, 2013; Woelfel et al., 2013). Goel (1995) finds that problem structuring typically occurs at the beginning of a design task, and periodically recurs when designers might need to understand the scope and features of the design problem. This recursive nature of problem structuring contributes to the iterative nature of the design process.

According to traditional Information Processing theories, this information should be seen as residing inside the mind of the designer; however, the findings of empirical studies on expert design behaviour show that designers also draw on externally-located sources of information (Haupt, 2013). Therefore, this observation necessitated the incorporation of the Embodiment Theory to empirically investigate how the Grade 9 participants might draw from externally-located sources of information. These external sources included external representations and visual elements in the technology learning environment.

The research findings suggest that little in the structure of design problems prescribes how designers should engage in problem structuring. Furthermore, literature from expert design cognition indicates that problem structuring is determined by the practice and expertise of designers (Goel, 1995; Vincenti, 1990; Haupt, 2013). It therefore seemed necessary to describe how technology learners use information to structure and transform ill-structured design problems.

Typical content that designers consider during problem structuring includes the users' needs and wants, design objectives, and the design problem context. However, designers might also consider elements of design solutions, in which Leaky phases are initiated.

### **b) Leaky phases**

'Leaky phases' denotes the overlap between problem structuring and solving (Goel, 1995; Haupt, 2013). Design cognition literature suggests that during problem solving, designers' understanding of the problem co-evolves with their understanding of the design solution (Kruger & Cross, 2006). As such, Leaky phases occur when designers engage in activities to find missing information about possible solutions while engaged in problem structuring. Similarly, Leaky phases also occur when designers might try to find missing information about the problem while paying attention to generating solutions or developing design ideas.

In this study, problem solving was also seen in conjunction with problem structuring as the solutions developed by novice and expert designers lacked depth and richness (Goel, 1995; Haupt, 2013). This lack of depth and richness is also evidenced in the type of external representations that designers make in the form of rough, ambiguous and non-specific sketches. These external representations are gradually developed in terms of detail when designers compare design solutions to the context of the problem, and the people and objects involved in the design problem context (Love, 2002). Information about the problem context is typically explored during the problem structuring phase of the design process. This backward and forward movement during the problem structuring and problem solving phases typically implies and contributes to the iterative nature of design processes (Goel, 1995; Haupt, 2013; Kimbell & Stables, 2008).

### **c) Problem solving**

During the early phases of the design process, problem solving can be categorised into three different sub-phases according to the level of detail involved in each sub-phase (Goel, 1995; Haupt, 2013). These three sub-phases are preliminary design, design development, and refinement (Goel, 1995). For the purposes of this study, I only focused on preliminary design, which forms part of the initial phases during a design process. Problem solving during the preliminary design phase of the design process is marked by designers' ability to generate and explore alternative solutions that surface during the problem structuring phase, or when designers develop proposed design ideas (Goel, 1995; Haupt, 2013).

Typical content that designers consider during problem solving includes the function, behaviour and structure of possible design solutions. However, designers might also consider elements of the design problem in which Leaky phases are initiated.

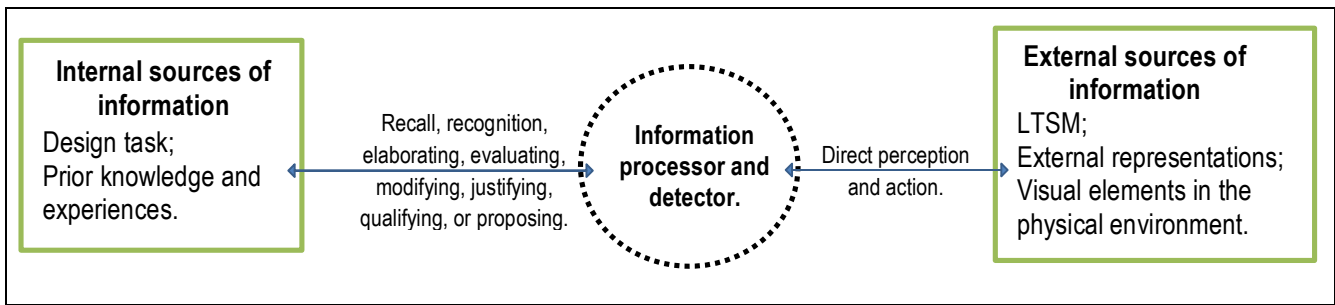
#### **2.4.4 The extended design task environment**

Design task environments, as conceptualised by Goel and Pirolli (1992), denote a theoretical construct for describing the design problem, goal and other relevant factors impacting on the designer's access to and use of information sources. However, in Section 2.3.1, I identified a limitation of Goel and Pirolli's (1992) notion of design task environment as its inability to describe how designers access and use external sources of information to structure and solve design problems. I accordingly adopted Haupt's (2013) conceptualisation of the extended design task environment to include the Embodiment Theory in order to account for technology participants' access to and use of external sources of information. Nevertheless, I still relied on two of the twelve common features identified by Goel and Pirolli (1992) that constitute the design task environment, which are discussed in Section 2.3.1, namely, the availability of information, and the notion that design problem solving activities start with input information about a problem and end with an output of design specification.

##### **d) Availability of information**

During design tasks, the information contained in the extended design task environment is limited, i.e. unknown or incoherent (Visser, 2010; Lawson, 2006). Designers therefore constantly engage in information-searching activities within the extended design task environment in order to decrease uncertainty, which helps them structure and solve design problems.

I accordingly assumed that when given the data collection instrument, i.e. the design task (see Chapter 3, Section 3.6.2), the participants would be compelled to search for relevant sources of information to structure and solve their given design problem. In planning the ill-structured design task to be given to the participants of this study, I assumed that specific internal and external information sources would be accessed and used during the participants' design processes. I considered internal sources of information to be information specified in the design task and information stored in the memory of the participants. Furthermore, I considered external sources of information to be information contained in Learning and Teaching Support Materials (LTSM), the external representations that the learners made, and information detected in the physical environment. Methodologically speaking, I had to provide participants with a design task that allowed them to access and use both internal and external sources of information in order to structure and solve the ill-structured design problem. Integrating the Information Processing and Embodiment theories implied that I viewed participants both as information processors and as detectors within the extended design task environment, as depicted in Figure 2.9.



**Figure 2.9: Processing and detecting internal and external sources of information**

When viewing the participants as information processors, I assumed that the participants might access and use internal sources of information in the extended design task environment by using the internal strategies discussed in Section 2.3.1. These internal strategies include recall, recognition, elaborating, evaluating, modifying, justifying, qualifying and proposing. In addition to this, when viewing participants as information detectors within the extended design task environment, I assumed that the participants might access and use external sources of information by interacting with the environment perceptually and physically. Specifically, I selected two aspects prominent in the Embodiment Theory to describe participants' perceptual and physical interaction with their technology learning environment. These two aspects are affordances and perception-action cycles, which were previously discussed in Section 2.3.2.

### **Affordances**

Affordances are defined as properties in the physical environment that can be discovered through perceptual activities (Gibson, 1986). Affordances in relation to physical objects mean possibilities for action that objects may permit (Gibson, 1986). In terms of a technology learning environment, this means that visual elements in the learning environment, i.e. states of matter, surfaces and textures, may provide learners with innumerable cues or triggers for actions and behaviour (Gibson, 1986) in order to solve design problems (Barab & Roth, 2006; Kulikowich & Alexander, 2010). For example, technology learners might perceive the shape and size of a pencil, which they associate with a log that affords lifting, and use the pencil to elaborate on the different ways in which a lifting machine may be able to lift logs. Affordances therefore emerge in relation to the learners' ability to perceive physical properties of the environment and act thereon. As such, problem structuring and problem solving behaviour is influenced by the availability of affordances in the physical environment, and by learners' ability to recognise these affordances (Kulikowich & Alexander, 2010). Methodologically, this meant that I had to individuate instances where the participants interacted with the physical technology learning environment during the design task in order to contribute information that would help them to structure or solve their design problem.

### **Perception-action cycles**

Affordances logically relate to perception as they need to be perceived in order to result in action. Embodiment theories define perception as “our means of keeping in touch with the world, of obtaining information about the world and where we are in it” (Gibson & Pick, 2000, p. 3). Perceiving is also an active process rather than a passive process of receiving information. This implies that learners might actively seek information by doing something to obtain information, for example, turn their heads, draw a line, or turn a page (Adolph & Kretch, 2015). The theory of Embodiment suggests that learners might rely on external structures in the environment when they encounter a cognitive burden. As such, learners might use the environment as external scaffolding to ease cognitive processing (Calonius, 2013; Clark, 2008; Hill, 1998; Wilson, 2002). The notion of scaffolding is derived from the developmental psychologist Lev Vygotsky, who argued that external structures may aid in the development of cognitive capacities (Calonius, 2013). For example, technology learners might decide to use a highlighter to indicate important information in a design task. As a result, learners may later refer back to the highlighted text if they search for important information. In essence, the notion of cognitive scaffolding refers to the utilisation of external material resources to aid in cognitive processing (Clark, 2008; Kirsh, 2010; Kirsh & Maglio, 1994; Lewis, 1999). Although I acknowledge that scaffolding may refer to social structures such as peers, educators or parents, social cognition was not the focus of this study. I only focused on embodied material information within the technology participants' learning environment.

Perceptual activity also guides action within a changeable environment on the basis of access to information about objects, events and places, and what the perceiver can do about the perceived information. Therefore, perception and action are a cyclical process in which perception accesses information for action, and action has consequences for perception (Gibson, 1997). The implication of this notion of perception-action for this study was that I looked for instances where the technology participants structured and solved design problems by means of perception and action activity (Richardson et al., 2008). For example, participants regularly perceived and evaluated external pictorial information about existing products during the problem solving cognitive phases (see Chapter 4). By perceiving the information embodied in external pictorial information, the participants had the ability to make temporary design decisions. These design decisions in turn influenced the subsequent information that was accessed and used by the participants. I could potentially find evidence for action on perceptual information in the external representations that the participants made. The external representations included talking, sketching, writing and 3D modelling. This implied that I had to sequentially track where participants directly perceived embodied information in the physical environment, and the subsequent external representations that followed.

The value of the Embodiment Theory for cognition lies in the way it defines the learning environment and the significance it places on the interactions between learners and their external environment. Learners are seen to be an integral part of the learning environment and are therefore inseparable from natural, technological, social, historical, cultural and political technology learning environment elements (Petrina et al., 2008; Kangas et al., 2013). Furthermore, the learners' experiences with these learning environment elements are to be understood not from a detached objective viewpoint, as described by the Information Processing theories of designing, but from the interactions between learners and embodied information. In order to highlight this integrative approach to the technology participants' design cognition, I viewed the participants both as information processors and as information detectors. I therefore identified instances where the participants in this study detected physical elements in the technology learning environment in order to contribute to how they internally processed information when structuring and solving their design problems. In turn, I also had to identify instances where the participants' information processing contributed to what external information they accessed and used.

#### **e) *Input/output***

Goel and Pirolli's (1992) characterisation of design task environments suggests that the design task, prior knowledge, and experience alone are the primary sources that designers draw on during the early phases of the design process. However, in her analysis of expert design cognition, Haupt (2013) argues that this does not represent a natural description of the information sources that designers actually draw on. Instead, Haupt (2013) argues that expert designers access and use external sources of information by integrating Embodiment theories to describe the design task environment of designers. Haupt's (2013) integration of Embodiment theories allowed her to investigate both the internal and the external sources of information that expert designers draw on in the extended design task environment. I was hence able to adapt this conceptual framework for use in the technology learning environment to investigate how novice designers access and use internal and external sources of information.

Figure 2.10 presents the integration of internal and external information sources in a technology learning environment. Input information is accessed and used from internal sources, i.e. the design task and learners' memory; and external sources, i.e. Learning and Teaching Support Materials (LTSM), external representations and the physical environment. Information is then transformed internally, i.e. by applying operators; and externally, i.e. perception-action, sketching, talking and 3D modelling. Finally, a design specification is produced as output information at the end of the design process.

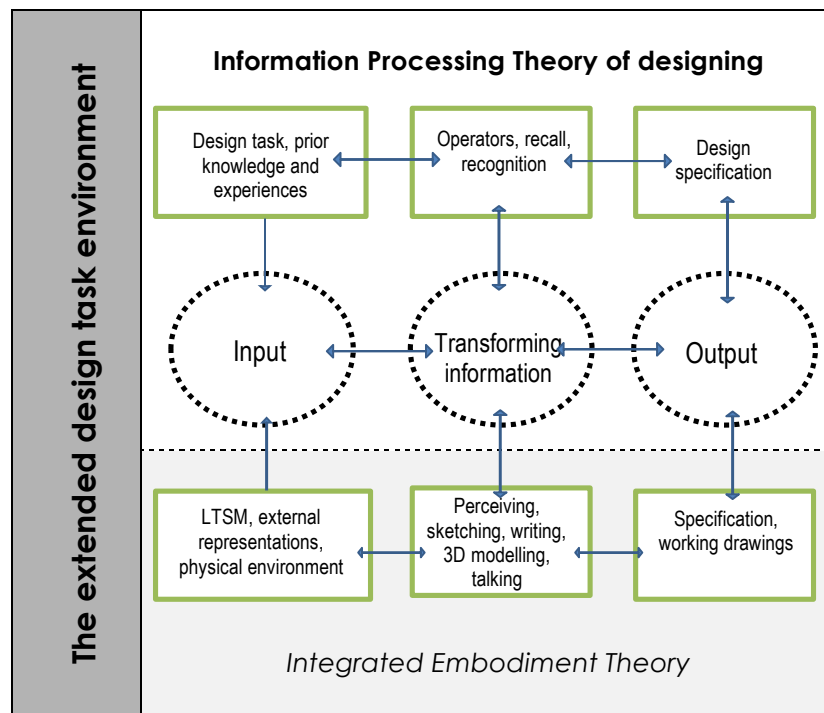


Figure 2.10: Design cognition as an input/output system

As discussed in Section 2.3.1, I only focused on input information and transformation, and not on output information during the design task, since output information does not form part of the early phases of the design process (Goel, 1995).

## 2.5 Conclusion

In this chapter I gave an indication of the developing field of research conducted on cognition in TE. Thereafter, I explored two main theoretical approaches for studying cognition, namely, the Information Processing and Embodiment theories. These two theoretical approaches were further described in order to construct an appropriate theoretical lens through which the information access and use of Grade 9 technology learners could be studied. Furthermore, I argued that it is necessary to integrate the theories of Information Processing and Embodiment in order to gain a deeper and rich understanding of design cognition. Subsequently, I adapted a conceptual framework from previous empirical research conducted on professional designers in order to justify the appropriateness of using the Extended Cognition framework for my study. In the following Chapter, I discuss and explain the methodological implications for examining the participants' information access and use during the early phases of their design.

## Chapter 3 : Research Methodology

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### 3.1 Chapter overview

In Chapter 2, I discussed the theoretical underpinning of the cognitive theories through which I could study the participants' information access and usage activities. These underpinnings served as the theoretical basis for the way in which I planned and conducted this empirical study. The purpose of Chapter 3 is to align the methodological choices that I made with the research questions and purpose of this study, which were presented in Chapter 1. I start this chapter by discussing my selected research paradigm, my approach and the design that I planned and implemented in this study. Accordingly, I explain my sampling procedures and the unit of analysis. Thereafter, I explain the process of data collection and analysis. I conclude this chapter with a discussion of the quality assurance measures I took and the ethical guidelines I adhered to.

### 3.2 Paradigmatic approach

Research methodologies are assumed to be embedded in a paradigmatic viewpoint, serving as the fundamental beliefs and assumptions through which educational researchers perceive and understand the world, and hence serve as a framework for thinking and guiding behaviour during research (Creswell, 2014). This study was embedded in a pragmatic worldview. Essentially, a pragmatic worldview is not easily defined, since it encompasses a wide variety of philosophical standpoints (Creswell, 2014). In this section (3.2), I discuss the main characteristics underlying a pragmatist worldview, and give reasons for adopting it in this study.

Pragmatism as a research paradigm arose from the works of James (1907), Dewey (1931) and Pierce (1931). A common theme among these thinkers was their rejection of traditional epistemological, methodological and ontological assumptions when investigating phenomena (Creswell, 2014). They believed that meaningful research should be rooted in practical application and not only restricted to explanations, i.e. post-positivist assumptions, or deeper levels of understanding, i.e. constructivist assumptions (Goldkuhl, 2012). This belief seemed to fit my own values as a researcher, since I wanted not only to understand how the participants accessed and used information through the lens of Extended Cognition, but also to develop practical guidelines that might contribute to effective design cognition facilitation. Developing practical outcomes in research, such as these guidelines, is one of the key characteristics of a pragmatic approach (Creswell, 2014; Goldkuhl, 2012).

These guidelines that I developed could be used to effectively facilitate the problem structuring and solving phases of technology learners during the early phases of their design processes. In developing these guidelines, I addressed my primary research problem, discussed in Chapter 1 (Section 1.3), which I identified as an apparent lack of guidelines in the technology CAPS document to facilitate technology learners' information access and use activities during the early phases of their design processes.

I adopted the views of Tashakkori and Teddlie (1998, 2003), who believe that pragmatism is essentially a research paradigm in which researchers address their research problem by using, *inter alia*, a variety of qualitative and quantitative data sources, multiple methods to collect data, and multiple perspectives to interpret the data. For this study, I accordingly adopted a pragmatic worldview by:

- (1) Collecting multiple data sources to address my research problem, i.e. examining how the participants accessed and used information during the early phases of the design process. These data sources were both quantitative and qualitative in nature, and will be discussed in Section 3.3.
- (2) In addition to this, I used multiple perspectives to interpret the data for this study. This was done from an amalgamated view of the Information Processing and Embodiment theories. The Information Processing Theory is essentially a post-positivist theory of design cognition, while the Embodiment Theory has its roots in constructivism (Petrina, 2010). The implications of these perspectives for my data interpretation are discussed in Section 3.7. Furthermore, using multiple perspectives contributed to theoretical triangulation for this study, which will be discussed in Section 3.8.
- (3) The amalgamation of the Information Processing and Embodiment theories also necessitated different data collection methods. Since Information Processing Theory aims to describe the internal cognitive processing of learners, and Embodiment theories the external information detection of learners, I needed multiple data collection methods that would evidence both perspectives. Therefore, my pragmatic viewpoint encouraged me to adapt conventional methods of protocol studies in order to collect data, evidencing both the internal and the external cognitive processes of the participants. In the past, Think-Aloud Protocol Studies (TAPS) were conducted in laboratory settings and were used to collect data from individual participants only (Ericsson & Simon, 1993; Goel, 1995; Craig, 2001). For my study, I decided to conduct TAPS with groups of participants instead of individual participants (see Section 3.6.1).

Furthermore, I also decided to conduct TAPS in participants' familiar technology learning environment. Justifications for these methodological decisions are further discussed in Section 3.6. By using a TAPS methodology, I was able to collect data revealing both internal information processing and external information detection. By using multiple data collection methods, I enhanced the methodological triangulation of this study, which is discussed in Section 3.8.

In the next section, I discuss the underlying metaphysical assumptions of pragmatism, and relate these assumptions to the scope of my study.

Ontology signified my view of the nature of reality, and refers to the assumptions that I made about the reality in which the world works (Guba & Lincoln, 2005; Saunders et al., 2009). Pragmatism allowed me to consider that the design cognition of the participants constitutes both internal and external realities. The Information Processing Theory guided me to empirically study the internal realities of the participants by providing a framework to empirically study how information sources were processed internally. In that way, I was able to study the internal reality that contributed to the participants' design cognition. Additionally, the Embodiment Theory guided me to empirically investigate the external realities of the participants by providing a framework to study how information sources are detected externally. I was thus able to study the external reality that contributed to the participants' design cognition.

Epistemology refers to the nature of knowledge and what I deemed as acceptable knowledge in this study (Guba & Lincoln, 2005; Saunders et al., 2009). Furthermore, my epistemological viewpoint emphasised what I considered as identifiable knowledge (Guba & Lincoln, 2005; Saunders et al., 2009). From a pragmatic viewpoint, I considered both unobservable and observable cognitive processes to signify knowledge that can contribute to my understanding of the participants' design cognition. I relied on my theoretical understanding of the Information Processing Theory to collect evidence that reflected the unobservable cognitive processes of the participants. I was able to describe the unobservable cognitive processes by referring to theoretical constructs, including the design problem solving space, and the design task environment. Furthermore, the Information Processing Theory allowed me to infer unobservable processes by relying on the external representations that the participants made. Moreover, I relied on my theoretical understanding of the Embodiment Theory to collect evidence of the observable cognitive processes of the participants. I was able to describe the observable cognitive processes by observing the participants' design processes and identifying instances where the participants perceived meaningful information and acted thereon by talking, sketching, writing, and 3D modelling.

Methodology refers to the methods through which knowledge might be gained (Guba & Lincoln, 2005; Saunders et al., 2009). Pragmatism allowed me to mix methods in order to address my research question (Tashakkori & Teddlie, 1998). I specifically found the concurrent mixed methods approach useful because it allowed me to collect multiple sources of qualitative and quantitative data. In that way, I was able to collect confirmatory instances of the participants' internal and external cognitive processes. The qualitative and quantitative nature of this study is discussed in the next section (3.3).

Axiology encompasses the role of values during a research investigation and refers to the stance I took towards the data that I investigated. Therefore, my role as the researcher was defined by the objective and subjective stance that I took when investigating the participants' design cognition (Guba & Lincoln, 2005; Saunders et al., 2009). On the one hand, pragmatism allowed me to view data about the participants' cognitive processes objectively, i.e. independently of human consciousness. Therefore, I viewed the sequence of each design process objectively by constantly referring to temporal data about each cognitive action in the timeframe in which it occurred. On the other hand, pragmatism also allowed me to view data about the participants' cognitive processes subjectively. Therefore, I relied on the conceptual framework of this study to interpret the participants' verbal utterances during their design tasks on the basis of my understanding of the Information Processing and Embodiment Theory. By relying on the conceptual framework of this study, I attempted to take a neutral stance toward interpreting my data.

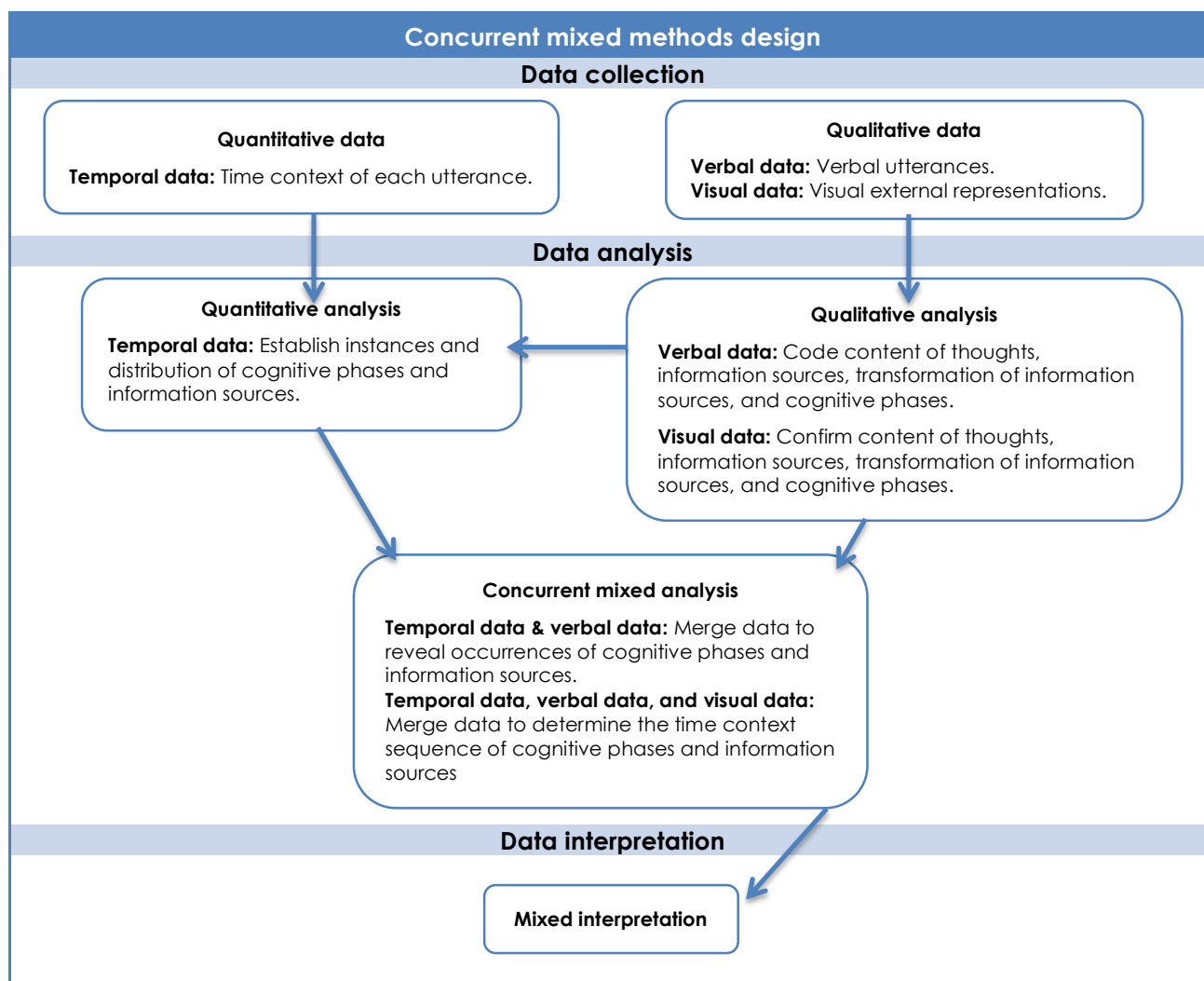
### **3.3 Research approach**

On the basis of my research questions, stated in Section 1.6 of Chapter 1, and my pragmatic assumptions, discussed in Section 3.2, I needed a combination of qualitative and quantitative approaches during the data collection and analysis in order to address my research questions. My research approach was hence informed by a concurrent mixed methods design in which qualitative data took prominence (QUAL-quant) (Creswell, 2014). By mixing quantitative and qualitative data collection and analysis methods, I strove not only to provide rich descriptions of the participants' design cognition, but also to enhance the trustworthiness of this study. For this study, I subscribed to Denzin's (1970) notion of methodological triangulation. Methodological triangulation in this study implied that I used more than one method for data collection and analysis. I discuss the quality measures further in Section 3.8.

Following a concurrent mixed methods design implied that I simultaneously collected quantitative and qualitative data (Tashakkori & Teddlie, 2003). In my study, I collected qualitative verbal and visual data types, and quantitative temporal data. Due to the implicit nature of thinking, it was not possible for me to show everything that the participants thought of (Ericsson & Simon, 1994). Therefore, it was important to collect as many data types as possible that might show evidence of internal processing in order to adequately address my research questions. Collecting multiple types

of data at the same time helped me to provide a rich account of the participants' information processing and detecting behaviour. As such, a mixed methods approach seemed most appropriate since I could collect multiple data types, and engage in deeper levels of analysis by mixing quantitative and qualitative analysis methods, which a single approach would not have allowed me to do (Creswell, 2014).

Figure 3.1 presents an overview of the concurrent mixed methods research approach that I followed during this study. I discuss this approach for the remainder of this section.



**Figure 3.1: Concurrent mixed methods research design**

I simultaneously analysed and interpreted the quantitative and qualitative data (Tashakkori & Teddlie, 2003). My final inferences were accordingly based on both data analysis results. I was able to analyse the verbal utterances of the participants both qualitatively and quantitatively. I analysed the verbal utterances of the participants qualitatively by coding instances of cognitive phases, information sources, and transformation of information respectively. By analysing the verbal data qualitatively, I was able to infer (1) the cognitive phases that the participants engaged in; (2) what

information sources they accessed and used, and (3) how they transformed their understanding of the design problem and its possible solutions. In addition to this, by coding verbal data qualitatively, I was able to count instances of cognitive phases, information sources and transformations. I used these counts to describe the frequency and distribution of the cognitive phases and information sources. I was consequently able to address my first sub-research question, namely, 'What information sources do learners access and use during the early phases of the design process?' I also used visual data to confirm the inferred cognitive phases and information sources and actions taken thereupon by examining the participants' concurrent external representations in the form of writing, sketching and 3D modelling, captured on a video recording.

Once I was able to merge the temporal, verbal and visual data, I was able to qualitatively analyse the contextual sequence in which the participants accessed and used information to structure and solve their design problems. In this way, by capturing the external representations of the participants in conjunction with their verbal utterances on video, I was hence able to address my second and third sub-research questions, which were: 'How [do] learners access and use internal and external information sources when structuring design problems?' and 'How do learners access and use internal and external information sources when solving design problems?' respectively.

By only using a quantitative approach, I would not have been able to qualitatively analyse (1) the verbal utterances of the participants, showing evidence of how problem structuring and solving transformed the ill-structured problem solving space, (2) the internal and external sources of information accessed and used in the extended design task environment during problem structuring and solving, or (3) how sources of information were accessed and used by participants.

Using only qualitative methods would not have been sufficient to address my research questions, since I needed to analyse the time context of each verbal utterance, contained in the temporal data, and count the occurrences of participants' cognitive phases and actions. Therefore, my data analysis and interpretations were dependent on describing (1) the sequences of cognitive actions, by using temporal data, (2) the frequency of each cognitive phase that the participants engaged in, evidencing the development of the design problem solving space, and (3) the frequency of information access and use, demonstrating how participants accessed and used information sources from the extended design task environment. Counting instances of cognitive phases helped me to reveal how often, if at all, participants engaged in problem structuring and solving. Counting instances of cognitive actions allowed me to describe the frequency of the participants' information access and use during the early phases of their design processes.

### 3.4 Research design

For this study, I considered a case study using a concurrent TAPS methodology to be the most appropriate research design. Planning to implement a case study research design had several implications for my study. These implications can be summarised as the following issues: appropriateness of this study to use a case study design, identification of cases, using purposeful sampling, collecting multiple sources of data, conducting a holistic data analysis, and interpreting the meaning of each case (Creswell, 2014; Yin, 2014; Guba & Lincoln 2005).

Conducting a TAPS process with the selected cases allowed me to study an issue microscopically within a bounded system (Yin, 2014; Creswell, 2014). For this study, I considered the 'issue' to entail the design cognition of the participants during the early phases of the design process and considered the 'bounded system' to signify the natural<sup>5</sup> technology learning environment in which I would study design cognition. Furthermore, I identified cases consisting of groups of Grade 9 technology participants. I considered each group of participants to be sharing the same intention as they structured and solved their design problems. I decided on groups of participants rather than individual participants as the case to be investigated because I wanted to maximise the verbal fluency among the participants during their TAPS. In the past, TAPS was often based on the design cognition of individual designers (Craig, 2001). As such, the quality of the data collected was questioned because thinking aloud was regarded as an unnatural activity during individual designing (Ericsson & Simon, 1993). Welch (1999) also recommends that by studying groups of participants instead of individuals, a researcher creates an environment that is conducive to thinking out loud. By modifying conventional TAPS, and focusing on groups of participants, I enhanced the external validity of the data collected as the participants were accustomed to addressing design tasks collectively (DoBE, 2011). Moreover, working in a group required the participants to communicate their thoughts to each other, thereby reducing the oddness of thinking aloud.

For this study, I stipulated specific criteria for selecting the sample purposely. These criteria included: the participants should have the ability to communicate their design ideas effectively to each other, they should be able to work together as a group, and they should have above-average design capability. These criteria are further discussed in Section 3.5.2.

Case study designs further allow researchers to collect multiple sources of data in order to give an in-depth description of each case to be studied (Yin, 2014; Creswell, 2014). This allowance resonated with my pragmatist research paradigm in terms of my requirement for various types of data to describe how information sources contributed to the participants' transformations during the early

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<sup>5</sup> Natural technology learning environments in this study signified (1) the participants' regular venue where they received technology tuition, (2) a technology classroom environment containing participants' familiar sources of information, as opposed to a laboratory setting used for conventional TAPS.

phases of their design processes. I was accordingly able to collect verbal, visual and temporal data, which is discussed in Section 3.6. These data types could also be analysed by integrating qualitative and quantitative approaches. I elaborate on these analysis approaches in Section 3.7. Additionally, I also sought to enhance the trustworthiness of this study by using methodological triangulation, which is discussed in Section 3.8.

Finally, a case study research design requires researchers to constructively interpret the cognitive processes involved in the early phases of design processes (Creswell, 2014; Yin, 2014). To this end, each case was interpreted by continuously referring to the conceptual framework of this study, which was discussed in Chapter 2, Section 2.4. This means that I interpreted the verbal, visual and temporal data through the lens of the Extended Cognition theory.

Having framed my research paradigm, research approach and research design, I was able to plan my data collection strategy. Table 3.1 represents the research process that I followed in order to address the research questions, as discussed in Chapter 1 (Section 1.7).

**Table 3.1: The research process followed in this study**

<b>Phase 1 Initial exploration of the field</b>			
<b>Strategies</b>		<b>Purpose</b>	<b>Rigour</b>
<b>Visual explorations of different technology learning environments.</b>  <b>Literature survey.</b>		Interviews with technology teachers and familiarising myself with Grade 9 prior knowledge and design skills. Observing naturalistic technology learning environments.  Investigating the technology CAPS document and prescribed textbooks. Extensive literature study on design cognition.	Rich contextual descriptions for transferability.
<b>Phase 2 Sampling</b>			
<b>Strategies</b>	<b>Approach</b>	<b>Purpose</b>	<b>Rigour</b>
<b>Purposeful sampling.</b>	<b>QUAL:</b> Small samples of participants. <b>Quan:</b> Large samples of data.	Selecting appropriate cases to study in order to address the research questions.	Trustworthiness; Transferability; Credibility.  Richness of data; Validity; Reliability.
<b>Phase 3 Data collection</b>			
<b>Strategies</b>	<b>Approach</b>	<b>Purpose</b>	<b>Rigour</b>
<b>Conduct TAPS by using the adapted design task from the prescribed DoBE textbook.</b>	<b>QUAL:</b> Collection of verbal and visual data; Capturing visual data in photographs. <b>Quan:</b> Temporal data.	Introducing the participants to the design task in order to elicit cognitive phases when accessing and using information sources.	Ensuring naturalistic execution of design task.  Trustworthiness; Dependability; Credibility; Transferability.
<b>Phase 4 Data structuring</b>			
<b>Strategies</b>	<b>Approach</b>	<b>Purpose</b>	<b>Rigour</b>
<b>Constructs from the conceptual framework.</b>	<b>QUAL:</b> Segmenting verbal data into utterances based on the content of thought processes. <b>quan:</b> Segmenting verbal data into temporal instances.	Individuation of utterances into cognitive modules for microscopic investigation of participants' cognitive processes.	Limiting researcher bias.  Maximising neutrality.  Construct validity.
<b>Phase 5 Data analysis and interpretation</b>			
<b>Strategies</b>	<b>Approach</b>	<b>Purpose</b>	<b>Rigour</b>
<b>Constructs from the conceptual framework.</b>	<b>QUAL</b> Coding cognitive phases, information sources, transformation of information sources. Confirm in visual data. <b>Quan</b> Instances and distribution of cognitive phases and information sources. <b>Mixed</b> Merging data to reveal occurrences of cognitive phases and information sources.	Identifying observable evidence of constructs embedded in conceptual framework: <ul style="list-style-type: none"> <li>• Cognitive phases;</li> <li>• Internal and external information sources;</li> <li>• Operators; and</li> <li>• Mode of output.</li> </ul>	Limiting researcher bias.  Maximising neutrality.  Reliability.  Construct validity.  Confirmability.
<b>Phase 6 Reporting and dissemination</b>			
<b>Strategies</b>	<b>Approach</b>	<b>Purpose</b>	<b>Rigour</b>
<b>Constructs from the conceptual framework.</b>  <b>Tables and graphic representations.</b>	<b>Mixed</b> Narrative account of participants' design processes.  Presenting occurrences of early phases.  Presenting occurrences of information access and use.	Describing the design cognition of the participants.  Integrating Qual and Quan findings.  Identifying patterns and themes.  Presenting guidelines for the effective facilitation of early phases of the design process.	Confirmatory triangulation.  Researcher reflexivity.  Trustworthiness Construct validity.

## 3.5 Sampling

### 3.5.1 Target population

The target population for this study comprised one high school technology classroom, situated in a low socio-economic status public school. The Grade 9 participants were selected purposefully on the basis of their involvement with technology for approximately 3 years. I confirmed with the technology teacher that the members of the target population had already been exposed to at least six different design projects throughout their school careers. Furthermore, the technology teacher also informed me that the target population possessed the necessary design skills to complete the design task, including investigating, designing, making, evaluating, and communicating (DoBE, 2011), and conceptual knowledge about mechanical systems and control.

Prior to participating in this study, the target group completed their term 2 work, focusing on the mechanical systems and control content area<sup>6</sup>. The term was sequenced over eight weeks, comprising 20 contact lessons. During the lessons in weeks 1-4, the target group was introduced to a range of mechanical systems and control concepts, building on their Grade 8 work. These mechanical systems and control concepts included the following conceptual knowledge (DoBE, 2011, p. 53):

- Hydraulic/pneumatic systems that use restrictors, one-way valves: hydraulic press/jack;
- Gear systems – spur, bevel, rack and pinion, worm;
- Mechanical control mechanisms – ratchet and pawl; cleats; bicycle brakes; disc brakes;
- Belt-drive systems with more than one stage;
- Pulley systems – fixed pulley, moveable pulley, and multiple pulleys (block and tackle); and
- Systems where mechanical, electrical or pneumatic systems are combined.

The teacher taught these concepts to the target group mainly from a textbook (Clitheroe, Goosen, Kathan, Mlambo, Roebert & Sargeant, 2013) while they completed enabling tasks<sup>7</sup>. During weeks 5-8, the target group completed a Mini-Practical Assessment Task (Mini-PAT)<sup>8</sup> in groups of four with the aim of designing and making a 3D model of a hydraulic water pump, drawing on their prior knowledge of integrated mechanical systems and previous design skills. No tools and materials were

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<sup>6</sup> In technology there are four content areas, namely Processing, Structures, Mechanical systems and control, and Electrical systems and control (DoBE, 2011, p. 10).

<sup>7</sup> Enabling tasks are "activities used to teach then practise specific skills in preparation for a more advanced task" (DoBE, 2011, p. 13).

<sup>8</sup> A Mini-PAT is a "set of short practical assessment tasks which make up the main formal assessment of a learner's skills and application of knowledge during each term. It may be an assignment covering aspects of the design process, or it may be a full capability task covering all aspects of the design process" (DoBE, 2011, p. 13).

provided by the school for the target group to make their 3D models of the water pump; the learners therefore had to source their own 'affordable and easily accessible' materials.

Table 3.2 provides an overview of the conceptual knowledge and design skills that are specified in the CAPS document for technology, which I expected the participants to be engaged with prior to the study. For my study, I only listed the design skills linked to the early phases of the design process since these skills were the focus of my study. I assumed that the participants could draw on their prior knowledge and design skills to complete the prepared design task for my study.

**Table 3.2: Overview of conceptual knowledge and design skills**

Conceptual knowledge (DoBE, 2011, p. 53)	Design skills (DoBE, 2011, p. 49)
<ul style="list-style-type: none"> <li>• Gear systems – spur, bevel, rack and pinion, worm.</li> <li>• Mechanical control mechanisms – ratchet and pawl; cleats; bicycle brakes; disc brakes.</li> <li>• Belt-drive systems with more than one stage.</li> <li>• Pulley systems – fixed pulley, moveable pulley, and multiple pulleys (block and tackle).</li> <li>• Systems where mechanical, electrical or pneumatic systems are combined.</li> </ul>	<p><b>Investigate:</b> background context, nature of the need, environmental situation, and people concerned.</p> <ul style="list-style-type: none"> <li>• Locates and collects. Compares, sorts, verifies, evaluates (cross-checking different sources or resources) and stores information.</li> </ul> <p><b>Design:</b> people, purpose, appearance, environment, safety, real costs, ergonomics, quality, and production.</p> <ul style="list-style-type: none"> <li>• Write a design brief giving specifications and constraints (without assistance). Generate a range of possible solutions using sketches with explanatory notes. Select the most viable solution using well-reasoned argument.</li> </ul>

I also assumed that I would see evidence of the above mentioned knowledge and skills, shown in Table 3.2, during the participants' design task performance. My assumption was based on the fact that the participants had engaged with the conceptual knowledge and design skills in term 2, and should have had evidence thereof in their memories. Therefore, I acknowledged the conceptual knowledge as an internal source of information.

The participants from the target group had also been exposed to several external information sources during their design projects. These external sources included: a prescribed textbook; a workbook; Learning and Teaching Support Material (LTSM) such as worksheets, experiments and posters on the walls of the class; case studies investigated during their Mini-PAT; and books and internet sources found in the school's library. It should be noted that the research site for this study was situated in a low socio-economic area. Therefore, the quality of the external sources which students had access to was limited and considered to be of poor quality.

From an Information Processing viewpoint, this implied that the participants should be able to access and use prior knowledge from their memories to structure and solve the given design task for this study. From an Embodiment Theory viewpoint, this implied that participants might recognise concepts from mechanical systems and control from external information sources (Schwartz & Martin, 2008).

In Section 3.5.2, I discuss my methodology for sample selection. I also explain the unit of analysis for this study in Section 3.5.3, after which I discuss the data collection strategy in Section 3.6.

### 3.5.2 Sample

From the target population, purposeful sampling was used to select eight female participants (three groups of learners from different Grade 9 classes). At my request, the teacher from the secondary school selected eight top-performing and verbally fluent candidates. They were all female and from different classes. The sampling criteria that I gave to the teacher for participant selection included: the ability to communicate their design ideas effectively, the ability to work together as a group, and above-average design capability. These criteria were derived from the CAPS document for technology as examples of exemplary design capability behaviour (DoBE, 2011, p. 44).

The reason I only considered girls for the sample was supported by findings from Kimura (1992). Kimura found that girls performed better than males in tasks regarding perceptual speed, memory and verbal fluency. Verbal fluency was important for my study because the content validity of the produced verbal protocols depended on the participants' ability to fluently verbalise the content of their thoughts while recalling from memory and perceiving information from the external environment (Ericsson, 1993). Alternatively, males performed better in tasks related to visuospatial and mathematical reasoning (Kimura, 1992), which might be considered for studies during the detail design phases of the design process. However, detail design was not the focus of my study.

The eight participants selected by the teacher met the sampling criteria for this study. I expected that the selection of eight participants would be appropriate for my study for three reasons. Firstly, according to the teacher who selected the sample, all eight participants excelled in written examinations, being able to recall and explain concepts of mechanical systems and control. Secondly, the eight participants had worked together on their Mini-PAT in their previous term. I therefore anticipated that they would be able to work together effectively as a design team for my design task. Subsequently, the teacher conveniently clustered the eight participants into three groups: one group of two participants, and two groups of three participants.

Thirdly, the sample of eight participants had also achieved the highest marks for their Mini-PATs in the previous term, demonstrating their apparently exemplary design skills. The teacher selected these three groups to ensure enhanced verbal fluency between the participants.

### 3.5.3 Unit of analysis

For this study, the unit of analysis was the verbal utterances of each group of participants that were clustered into modules that I could interpret as cognitive actions. I applied a technique, adopted from Haupt (2013, p. 149), involving parallel qualitative and quantitative processes, which implied

that if a unit could be qualitatively distinguished, I could classify and count it. This resulted in my being able to quantify units, i.e. cognitive phases and sources of information, by counting and plotting their distribution throughout the participants' design processes. It further allowed me to qualitatively interpret the cognitive phases and sources of information by considering their contextual sequencing. More specifically, I attempted to identify and describe cognitive actions indicating:

- 1) Early phases of the design process (problem structuring and solving);
- 2) Which internal sources of information played a role in the transformation of participants' understanding of the design problem and possible solutions, and how this occurred; and
- 3) Which external sources of information played a role in the transformation of participants' understanding of the design problem and possible solutions, and how this occurred.

In the following section (3.6), I discuss the data collection strategy that I utilised to capture instances of participants' cognitive behaviours. I also discuss how I analysed and interpreted verbal and visual data types in Section 3.7.

### **3.6 Data collection method**

A Think Aloud Protocol Study (TAPS) is a strategy used for data collection that is used predominantly by cognitive scientists to explicate the inherent thought processes of participants engaging in problem solving activities (Ericsson & Simon, 1993). I regarded TAPS as the most appropriate method to collect evidence of the participants' internal and external cognitive actions because it allowed me to concurrently collect a verbal protocol of the participants' utterances, visual evidence of the participants' external representations, i.e. sketches, writings, 3D modelling, and temporal data of the participants' design task performance. The TAPS method requires participants of a study to talk out loud as they are performing a given task while being video recorded (Ericsson & Simon, 1993). This means that I required the participants to speak aloud as they progressed with their design processes in order to explicate their internal cognitive processes.

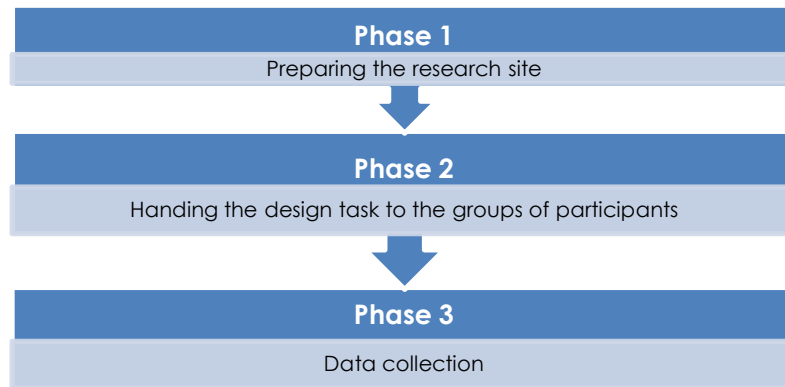
It was also important for me to capture the verbal utterances on video recordings so that I would be able to continuously revisit the data in the contextual sequence in which it occurred in order to enhance the credibility of my analysis. The video recordings helped me to frequently confirm the contextual sequencing of the participants' cognitive actions. I constantly reviewed what they pointed at, gazed at, gestured at, or any other action referencing the involvement of external sources of information.

At the same time, I was also interested in noting the involvement of internal sources of information. I inferred internal sources of information by noting the manner in which the participants recalled information and prior experiences from their memory. I also identified and described instances when the participants used information about the design problem context contained in their design tasks. Therefore, recording the sequence of cognitive activities was important for my study for two reasons. Firstly, the Information Processing Theory holds that learners serially process information during their design tasks (Newell & Simon, 1972). I therefore wanted to analyse how sources of information sequentially contributed to the participants' information access and usage activities. Secondly, the Embodiment Theory holds that during design tasks, learners might detect information from the external environment on which they could act, and subsequently detect additional information. I accordingly asked participants to explicitly say what they are looking at, thinking of and doing as they completed their design tasks, as recommended by Ericsson and Simon (1993). I was therefore able to analyse how the participants' actions contributed to the subsequent sources of information that were accessed and used.

I used the design task discussed in Section 3.6.2 as my data collection instrument to elicit the information access and usage activities of the participants. I was able to prepare a design task that complied with the requirements for ill-structured design problems (see Chapter 2, Section 2.2.2). In that way, I had control over the technology learning environment by giving the same design task to each group of participants and providing each group of participants with the same external sources of information. Therefore, I structured the technology learning environment for each group consistently. This implied that I strove for internal consistency when subjecting the participants to the design task. However, by giving each group of participants the same design task, I did not expect that they would access and use information sources in the same manner. I also did not anticipate that the participants from each group would generate the same solutions, which conformed to my understanding of ill-structured design problems.

### 3.6.1 Conducting TAPS

The purpose of the following section is to describe how I planned the actual data collection procedures of TAPS. Figure 3.2 represents the TAPS data collection procedures I planned for.



**Figure 3.2: The data collection procedures during TAPS**

During the first phase of TAPS, I prepared the research site to elicit participants' information access and usage activities (van Someren, Barnard & Sandberg, 1994). I considered that if I wanted rich data from each group of participants, I would have to create a naturalistic technology learning environment in which they felt comfortable (Trimmingham, 2008). In order to enhance the naturalistic technology learning environment, I recorded participants in their familiar technology classroom. As mentioned in Section 3.6.2, I also provided each group of participants with ordinary stationery items, including paper, pencils, pens, highlighters, rubber bands, post-it notes, page markers, paperclips and erasers. These stationery items also served a secondary function as potential 2D and 3D modelling materials during the execution of the design task. Another measure I took to enhance the naturalistic technology learning environment was to instruct participants to bring their technology workbooks along for the study. In that way, I ensured that there were familiar physical elements in the technology learning environment to put each group of participants at ease. In addition to this, I also provided each participant with a light meal during the late morning. I did this in order to sustain their energy during the TAPS process. Interferences during the recordings were kept to a minimum to ensure that the thought processes of the learners were not influenced (Ericsson & Simon, 1993).

Prior to recording each group of participants, I introduced the participants to the research setting, allowing them to familiarise themselves with the video recording equipment and the videographers. I deliberately introduced each group of participants to the two videographers present during the TAPS process in order to limit feelings of uneasiness caused by unfamiliarity. By helping the participants to feel at ease, and prolonging time spent in the research setting, I sought to reduce the "Hawthorne Effect" (Haidet, Tate, Divirgilio-Thomas, Kolanowski & Happ, 2009). This means that I wanted to reduce the participants' reactivity towards the videographers to ensure that they did not

alter their information access and usage activities through knowing that they were being observed. I also allowed each group of participants to ask questions about unfamiliar equipment in their technology class such as the video cameras and microphones. By asking questions, it seemed as if each group of participants became comfortable with the research setting. Photograph 3.1 shows the TAPS setup in which the information access and usage activities of the participants were recorded.



**Photograph 3.1: Photograph of the TAPS setup in a technology learning environment**

The second phase of the TAPS process commenced when I handed a group of participants their design task. After handing it to the participants, I read it aloud and emphasised the instructions and guidelines provided (see Appendix A). One of the reasons for providing guidelines in the design task is supported by Petrina et al. (2008), who state that adolescents need guidelines during a design process in order to guide their thinking processes. Another reason for clarifying guidelines and instructions was to maximise the quality of the verbal protocols (Miller & Brewer, 2003). I ensured that all members of each group of participants were clear about the instructions. I did this by allowing them to ask questions if they needed clarification before they started to work on their design task. I specifically tasked the participants to speak out loud in order to maximise the richness of the data collection.

The third phase of the TAPS process started when each group of participants engaged with the design task. I decided to video record each group of participants separately in order to optimally focus on each group's information access and usage activities individually. I hired two specialist videographers with two video cameras to record the design processes of the participants. I employed the videographers because I felt it was necessary for this study as I had decided to act as a participating observer and needed to rely on experienced professionals to capture the information access and usage activities of each group of participants. In a preparatory session, I specifically gave the videographers instructions in which I explained how I wanted them to capture the participants' design processes. One of the two videographers operated two fixed cameras in

order to document both macroscopic and microscopic views of the design activity. The macroscopic view documented the overall gestures and bodily movements of the participants, while the microscopic view documented their interaction with one another while talking, sketching, 3D modelling and writing. Although I did not analyse the bodily movement and gestures of the participants, I used them to contextualise utterances during TAPS. This meant that I specifically looked at what the participants looked at, pointed at, or gestured towards in order to identify the external sources of information that they accessed and used. In addition to this, the second videographer was responsible for controlling the quality of the video recordings by operating a sound mixer to enhance the sound quality of the video recordings.

The participants had one hour (equivalent to a double period of the technology subject) in which to complete the design task. I decided on a one hour time limit to ensure that a naturalistic account of the extended technology task environment could be adhered to. Time constraints were listed in the design task as well.

During the recording of each protocol, I acted as a participating observer while each group of participants executed their design task. As the participants engaged with the design task, the natural dialogue between the group members enhanced the verbal fluency of the participants' thoughts. At the end of the day, each TAPS produced one set of raw protocols, two videotapes of the participants' design processes, and sketches with written work. It is important to note here that I did not conduct a video analysis. I merely used the video recordings to contextualise the verbal utterances, which were the unit of analysis.

#### **a) Advantages of the TAPS method**

TAPS has been considered by some to be the most thorough account of how design problem solving might be studied (Craig, 2001). The reason for this might be attributed to the goal of protocol studies, which is to track and understand the reasoning and strategies that designers employ while engaged in design problem solving (Goel, 1995). Therefore, video recording the concurrent verbalisation and external visualisation during a delineated design task allowed me to document the moment to moment information access and usage activities of each group of participants during their design processes. This also meant that I was able to analyse how the participants engaged in problem structuring and solving by analysing the verbal utterances produced during TAPS.

### **b) Challenges of the TAPS method**

Aspects that I could identify in the literature constraining protocol studies of design activities included (Craig, 2001; Trimmingham, 2008):

- The obtrusive nature of video recording TAPS;
- The unnatural nature of thinking aloud during a design process; and
- The limitations of capturing data that evidences internal processing.

The first constraint of conducting protocol studies presupposes that the video recording of the TAPS process might be obtrusive and therefore influence the participants' behaviour and cognitive performance. In order to prevent this, I introduced the participants to the videographers who were recording the design tasks before the actual recording took place. I specifically explained the layout of the classroom to the participants, and allowed them to explore the research setting and to ask questions.

The second constraint has to do with the unnaturalness of thinking out loud during the design process. In order to deal with the effects of thinking aloud, I divided the eight participants in this study into three groups. Two of the three groups had three members, while the last group had two members. I deliberately divided participants into groups in order to create a natural dialogue between the members of each group. Therefore, I ensured that thinking out loud became a naturalistic activity, since each participant had to communicate their thoughts to the members of the group.

The third constraint deals with the limitations of capturing internal cognitive processes, since data collection methods are limited to audio, visual and tangible external representations. This implied that I only had access to the external representations of each group of participants' information access and usage activities, and had to make inferences about their unobservable internal cognitive processing.

### **3.6.2 Data collection instrument: The design task**

I adapted the design task from a textbook entitled "*Technology Today*" that was prescribed by the DoBE for Grade 9 learners in technology (Johnstone, Mitchley, Schreuder, Sherwood, Snyman & Ter-Morshuizen, 2013). This textbook was, however, not the same textbook that the target group was using for their Grade 9 curriculum, and the participants were therefore unfamiliar with the content of the design task that I gave them.

This strategy was advantageous because the textbook problem reflected the typical design problems that Grade 9 learners are exposed to in South African technology classrooms. In addition to this, by using this design task, I could expose the participants to an unknown design problem in which they had to apply their conceptual knowledge of mechanical systems and control. In the following sections, I give a detailed description of the design task that I used as the data collection instrument to elicit the information access and usage activities necessary to address my research questions.

To conduct the TAPS method, I gave each group of participants exactly the same design task to complete. In doing so, I expected that the semantic agreement between each group of participants should be high at the beginning of their design processes. This means that I subjected each group of participants to the same input information for their design processes (Summers, Joshi & Morkos, 2014). When each group of participants started with their design tasks, they progressed through their design processes differently. This difference could be linked to the different information sources that each group of participants accessed and used. These divergent thought progressions from each group could then be mapped in order to identify specific sources that contributed to the transformations in their understanding of the design problem and its possible solutions. The outcome of the design task involved the designing of a model of a mechanical lifting machine that would be able to lift logs from the ground onto a truck. The design task subsequently required the participants to design a model of a machine that could be used in a logging environment, and that could replace manual work by making work easier and faster.

The theoretical assumption I derived from the Information Processing Theory led me to assume that, when I provided the groups of participants with a design task as input information, they might immediately start with problem structuring and problem solving activities (see Chapter 2, Section 2.4). For this reason, I decided to plan an extended design task environment in which the participants were able to access and use internal and external sources of information. The detail of the design task is discussed in the next sections, with specific reference to a) the problem statement, b) instructions given to the participants in the design task, c) additional external sources of information provided in the design task.

#### **a) The problem statement**

The given problem statement contained in the design task included the following design problem in a logging context:

*A timber company cuts down trees in a forest and uses trucks to transport the logs to a nearby sawmill. It takes very long for workers to manually load the logs onto a truck one by one. The company needs a machine that can pick up logs from the ground and transfer them onto a truck quickly and safely (Johnstone et al., 2013).*

I decided to use this problem statement as the basis for the design task to find out about the information access and usage activities of the participants for two reasons. Firstly, it gave the participants an ill-structured problem statement that required them to understand the context of the design task and to solve the given problem by designing an artefact that could lift logs from the ground onto a truck. In terms of the Information Processing Theory, this meant that I deliberately gave the participants limited information in the problem statement, which meant that they needed to search for other input information in order to define their problem solving space (Goel, 1995). The participants therefore had to search, i.e. "investigate the background context, nature of the need, environmental situation, and people concerned" (DoBE, 2011, p. 49), by using their design skills. In turn, this enabled me to collect data about how the participants in each group structured their design problem. The specific design task for which each group of participants had to design a solution was articulated as follows:

*Design a model of a machine that can pick up logs from the ground and transfer them onto the transport truck. You only have to design the lifting machine, not the truck.*

For the design task, I did not disclose information about how the lifting machine should look or function so that the participants in each group had to design a machine according to their understanding of the design problem context. To this end, I provided pictorial information about mechanisms such as pulleys, gears, hydraulic systems, and gear and crank systems in order to trigger the participants' prior knowledge. In that way, I was able to collect data on how the participants of each group solved their design problem by accessing and using information. I ensured that the design task complied with the requirements stipulated in the CAPS document for technology at a Grade 9 level. The CAPS document for technology requires Grade 9 learners to (DoBE, 2011, p. 33): (1) "Investigate the situation so that an appropriate machine can be designed to solve the problem, need or want given in the scenario" and (2) "Investigate the possible mechanisms and controls to be used together to make the machine".

I aligned the design task according to the CAPS requirements by providing each group of participants with the design problem that was embedded in a real-life context. As a result, each group of participants had to investigate the situation and the design problem. The situation involved a logging environment in which trees are cut down in a plantation and need to be loaded up onto transport trucks. The design problem entailed the problem that current manual log-loading practices take a long time to lift the logs from the ground onto a truck. Hence, in the problem statement, the timber company needs a machine that will reduce the time taken by the manual log-loading practices by quickly transferring logs from the ground onto a truck.

The problem statement therefore seemed like an appropriate design task for the participants to complete since it provided a design problem situated in a real-life context, and could trigger curiosity about missing information that could lead to information access and usage activities. Essentially, by providing the socio-technological context, I anticipated that the participants would engage in problem structuring and problem solving activities. The context of the problem statement meant that learners might search for information about the environment in which the machine is required to function, how high the logs should be lifted, and what types of resources are available. I then also provided participants with instructions and guidelines to consider in their designs. These guidelines are discussed in the next section.

### **b) Instructions in the design task**

In the design task, I provided the participants with the following guidelines and instructions in order to guide them to access and use information sources:

**Table 3.3: Instructions and prompting guidelines given in the design task**

Instructions and guidelines in the design task	
1. Consider the environment in which the machine must function. Discuss the following questions: (15 minutes) <ul style="list-style-type: none"> <li>• How will the environment in which the machine will operate affect its operation?</li> <li>• Will the machine always stay in the same position?</li> <li>• How high will it have to lift the logs?</li> <li>• How will you ensure that the machine will not topple over?</li> <li>• How will the machine make work quicker and faster?</li> </ul>	2. Think about the movements your machine will need to perform. Which mechanisms can you use to: (20 Minutes) <ul style="list-style-type: none"> <li>• Pick up and hold the logs?</li> <li>• Lift the logs?</li> <li>• Create different movement in different parts of the machine?</li> <li>• Control the movements of the machine? (Gravity may cause the load to drop back and be damaged. Consider how to incorporate a control mechanism in your machine to stop this from happening).</li> </ul>
3. Suggest at least two possible designs that will be able to transfer logs from the ground onto a truck. (25 minutes)	

I ensured that the instructions displayed in Table 3.3 provided opportunities for both problem structuring and problem solving activities (Goel, 1995; Ollinger & Goel, 2010). In the first instruction, namely, “Consider the environment in which the machine must function. Discuss the following questions:” I anticipated that the groups of participants would engage in problem structuring activities. To this end, I provided prompting questions such as “How will the environment in which the machine will operate affect its operation?” for them to consider contextual information that was problem focused. I therefore expected the groups of participants to access and use information from internal and/or external sources of information.

In the second instruction, namely, *“Think about the movements your machine will need to perform:”* I intended the groups of participants to engage in problem solving activities. In this regard, I provided the participants with guiding questions, for example, *“Which mechanisms can you use to: Pick up and hold the logs?”* in order for them to focus on a solution, i.e. to consider information that would contribute to their conceptualisation of a structure with a function and behaviour that might address the design problem.

I also provided the groups of participants with time management guidelines in the instructions to ensure that they kept to the time constraints of the TAPS process. I considered these time management guidelines as contributions to the naturalistic technology learning environment because these time limits represented a one hour double period for technology.

Various design researchers acknowledge that the structure of the design task is situated in the mind of the designer (Eastman, 2001; Lawson, 2005; Dorst, 1997). Furthermore, information sources such as design requirements, constraints, and limitations are intrinsic to the design problem context (Eastman, 2001). In doing so, I acknowledged the design requirements implied by the guidelines in the design task as an internal source of information, concurring with other empirical design studies (Goel, 1995; Haupt, 2013). This meant that each time the participants made utterances related to a design requirement, for example *“How will the machine make work quicker and faster?”*, I regarded the participants' thoughts as emanating from an internal source of information, i.e. the design task.

### **c) Additional information in the design task**

I augmented the selected design task from the prescribed textbook (Johnstone et al., 2013) by adding external sources of information that I felt were lacking in the textbook. I gave the groups of participants a selection of external sources of information on the basis of my theoretical assumptions that were embedded in the Embodiment Theory, discussed in Chapter 2, Section 2.3. My assumption was based on how the Embodiment Theory describes learners as information detectors who are able to identify relevant information from the external environment in order to scaffold their problem solving activities (Kangas et al., 2013). I therefore gave each group of participants one document containing the following pictorial information:


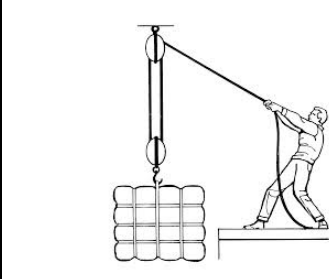

- Pictorial information about the problem context (e.g. the logging environment, logging workers);
- Pictorial information about possible mechanisms to be used (e.g. pulleys, gears, gear and crank systems); and
- Pictorial information about existing solutions (e.g. examples of lifting machines).

In addition to this, the participants had the following external sources of information available to them:

- 3D modelling materials which included basic stationery items and a Lego model of a fishing rod;
- Their own sketches created during the course of their design processes; and
- Their own Technology workbooks.

I specifically gave additional pictorial information sources to the participants because the design task, in its original form in the prescribed textbook, contained only one picture of a logging environment. I personally felt that this was not enough information to enable the participants to structure their design problem. I also provided additional information about possible mechanisms for lifting machines and existing solutions, since the original design task contained no pictorial information about lifting machines or the mechanisms used in lifting machines.

Figure 3.3 shows examples of the additional pictorial information with which I augmented the original design task.

		
<p>a) Pictorial information (Uisso, 2015), about the context of the design problem, i.e. how workers currently load logs from the ground onto the transport truck</p>	<p>b) Pictorial information (The Mighty Quill, 2014), about existing solutions, i.e. a pulley system as a means to lift heavy loads</p>	<p>c) Pictorial information (Automation components, 2012), about possible mechanisms to be used, i.e. a ratchet and pawl, used as a safety mechanism</p>

**Figure 3.3: Examples of external pictorial information provided in the design task**

Figure 3.3 represents three examples of pictorial information sources that I provided to each group of participants. I deliberately gave the participants these sources of external pictorial information for three reasons. Firstly, I wanted learners to be able to investigate the problem context, enhancing their problem structuring and problem solving cognitive phases. I could not, however, find sufficient information in the textbook about the problem, and therefore decided to look for relevant pictorial information about the problem context through internet sources. Secondly, I also included examples of mechanisms that would provide material scaffolding for the groups of participants. This was done so that they would be able to recall information about mechanical systems and control from their memories on the basis of the information they could detect in the pictorial information.

Thirdly, I also included examples of existing solutions to the design problem because few technology learners would have had access to information about the design problem context and possible solutions. This decision to include existing solutions is supported by the technology CAPS where it specifically states that learners should “evaluate existing products and processes” (DoBE, 2011, p. 9).

Furthermore, I also ensured a naturalistic technology classroom by providing each group of participants with a collection of stationery items typically found in a technology learning environment, including: pens, pencils, sheets of paper, highlighters, rulers, paper clips, glue, erasers, post-it notes, rubber bands, a Lego model of a fishing rod, plastic gears, and a pulley. By providing each group of participants with these basic stationery items, I anticipated that they might detect affordances in the stationery in order to build 3D models of design solutions. I also anticipated that the participants might create their own sketches from which they could structure and solve their design problems.

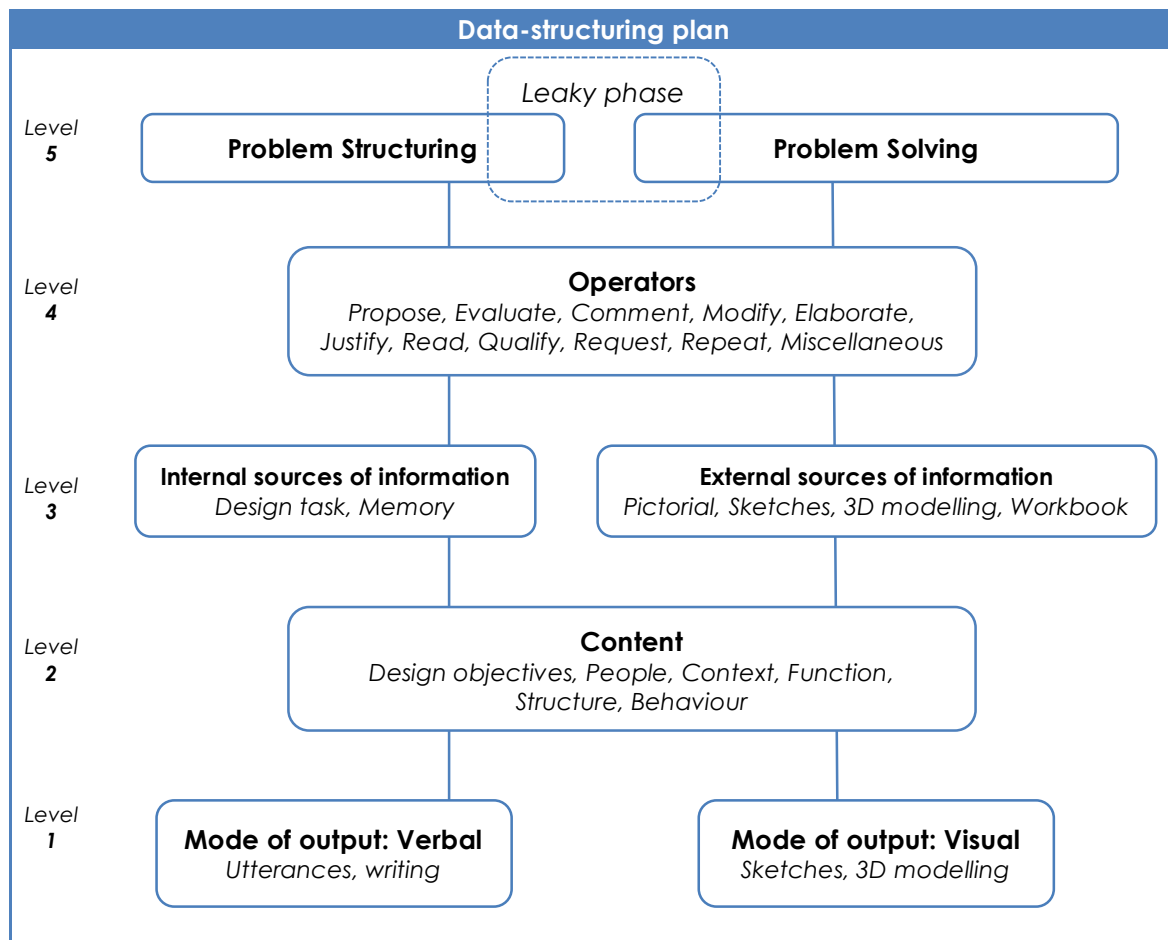
Prior to conducting TAPS, I also instructed the groups of participants to bring their technology workbooks to class, which contained their previous terms' work. In this regard, I expected that the participants might want to use a familiar source of information to structure and solve their design problems. I also regarded their workbook as contributing to a naturalistic technology learning environment.

### **3.7 Data analysis and interpretation**

After collecting data through TAPS, I commenced with the transcription of the video recordings and organisation of the visual data in concurrent sketches. I transcribed the recorded verbal protocols of the three groups of participants into textual data, which I could then analyse temporally and cross-reference with the writing, 3D models and sketches. Typing out the verbal protocols was necessary for me in order to ensure reliable coding procedures (van Someren et al., 1994). After transcribing the verbal protocols, I proceeded with the data analysis process. The purpose of the analysis for this study was not to generalise the findings, but to describe how each group of participants typically accessed and used sources of information to structure and solve their design problems. In the process of analysing both qualitative and quantitative data, I relied predominantly on concepts identified in the literature review and conceptual framework, which were described and explained in Chapter 2.

### 3.7.1 Qualitative data structuring and interpretation

I structured my qualitative data as illustrated in Figure 3.3. The data structuring plan consisted of five levels, which were derived from studies conducted on expert design cognition from an Information Processing viewpoint (Goel & Grafman, 2000; Goel et al., 2013; Goel, 1995). Therefore, I adapted the framework to include external sources of information, thereby including the Embodiment Theory in order to show how the participants engaged in design processes from an Extended Cognition perspective.



**Figure 3.4: The data structuring plan for this study**

**Level one** entailed coding the mode of output that each group of participants made during their completion of the design task. These modes of output included verbal and visual modes of output. I considered verbal output to encompass the utterances and writings that the participants made; and the verbal output to encompass the sketches and 3D models that the participants made during their design processes. I did not code the transformations involved in the participants' sketches or 3D models. I considered these modes of output only for confirmatory purposes in order to establish coherence between what the participants spoke about and how they visualised their understanding.

Segmentation was therefore based on the identification of the various themes contained in the content of the participants' thoughts, which I coded in Level 2. I needed to code the modes of output according to verbal and visual output so as to structure my data. In that way, I was able to utilise the verbal modes of output for interpretation purposes. I coded data logically and manually through the use of Microsoft Excel.

**Level two** entailed identifying the various themes contained in the content of the participants' thoughts, which I derived from the verbal data identified in Level 1. Identifying the themes of the participants' thoughts meant that I considered the differences and similarities of what the participants were thinking about while they were completing their design task. In order to identify the content, I used general themes from the literature on design cognition (Love, 2002; Goel & Grafman, 2000; Goel et al., 2013), which included design objectives, people involved, design context, behaviour of artefacts, function of artefacts and structure of artefacts.

I was able to interpret the content of the participants' thoughts when I identified the following key words as indicators of the themes in their thoughts; this is summarised in Table 3.4.

**Table 3.4: Indicators for identifying the content of the participants' thoughts**

Themes	Description	Words that acted as indicators
<b>Design objectives</b>	<i>Motives, intentions and goals of the designers.</i>	<i>We have to, it should be, faster, quicker, safe, easier, slow, difficult, dangerous, time, stability.</i>
<b>People</b>	<i>Users of artefacts, clients commissioning design work.</i>	<i>Workers, timber company, men, they, people, tired, person.</i>
<b>Context</b>	<i>The social and physical environment in which the designed artefact must function.</i>	<i>Environment, ground, truck, hill, logs, trees, how big and wide is the truck, place, cutting, weight.</i>
<b>Function</b>	<i>The desired or potential functionality the designed artefact should exhibit to address the design objective.</i>	<i>Pick up, lift, height, transfer logs, has to do.</i>
<b>Behaviour</b>	<i>The desired or potential behaviour the designed artefact is supposed to encourage.</i>	<i>Move around, lifting, up, down, left right, lift, operate, picking up, holding, pull, support, topple, fall.</i>
<b>Structure</b>	<i>The desired, proposed or potential physical form which the designed artefact should embody.</i>	<i>Machine, wheels, platform, gears, pulley, crank, cleat, ratchet, pole, hook, tongs, rope, mechanisms, seat, buttons.</i>

Table 3.4 summarises the description of themes identified in the design cognition literature, as well as the key words that I used to identify each of the themes. By coding the content of the participants' thoughts, I tried to establish what they were thinking about during their design processes. However, one limitation of this coding procedure was that each utterance that was made was heavily context specific. As a result, I had to consider the sequence in which utterances were made in order to take into account what happened before, during, and after each coded instance. Keeping track of the contextual sequence of utterances was enhanced by the use of video recordings.

I aimed to use the descriptions and keywords consistently so as to code the themes in the verbal utterances. Furthermore, I acknowledge that some verbal utterances contained more than one theme at a time, thus causing some degree of overlap between the themes identified in the participants' utterances. I accordingly coded these utterances with more than one content code.

Although the content of designers' thoughts was not part of my conceptual framework, I needed to code the content of the participants' thoughts in order to establish what information they were paying attention to while they were talking during their design processes. I needed to establish the content of their thoughts in order to determine what information sources they were potentially accessing and using during the design task. I coded these information sources in Level three.

**Level three** entailed coding the information sources that were accessed and used by the participants in the extended design task environment that seemed to contribute to the content of their thoughts in Level two. Internal sources included the design task and the participants' assumed memory. External sources included their workbook, sketches, pictorial information and 3D modelling materials (see Section 3.6). These information sources are discussed below in terms of how I coded each one in order to understand what sources of information the participants accessed and used. Although information access and usage are two separate activities, I only looked at instances where information was accessed to transform the participants' understanding of the design problem and its possible solutions. In this way, I assumed that when information was used, it was also accessed. Therefore, I did not report on information access activities in isolation.

It should be noted that I also revisited the video recordings of each group of participants' design processes while I coded the verbal utterances. In that way, I was also able to understand what the participants pointed at, gestured towards, held in their hands or gazed at. As such, I was able to enhance the consistency of my coding procedures.

#### ***Internal source: memory***

The first internal source that I coded entailed the participants' assumed memory. I looked for instances in which they could recall or recognise prior knowledge and experiences. I used the technology CAPS document as a reference tool to inform me about what the participants had learned during their Term 2 work (see Section 3.5.1). Table 3.5 presents a description of sources that I coded from memory, and the key words that I looked for in the verbal protocol to interpret the sources of information.

**Table 3.5: Indicators for identifying information access and use from memory**

Information source	Description	Words that acted as indicators
<b>Conceptual knowledge (DoBE, 2011)</b>	Gear systems – spur, bevel, rack and pinion, worm; mechanical control mechanisms – ratchet and pawl; cleats; bicycle brakes; disc brakes; belt-drive systems with more than one stage; pulley systems – fixed pulley, moveable pulley, and multiple pulleys (block and tackle); systems where mechanical, electrical or pneumatic systems are combined.	Remember (concept). When did we do (concept)? What do you call (concept)? Our teacher said that, where in the workbook is (concept)? What was that (concept) that we built? It was like (concept).
<b>Procedural knowledge (DoBE, 2011)</b>	Locates and collects. Compares, sorts, verifies, evaluates (cross-checking different sources or resources) and stores information; gives specifications and constraints (without assistance). Generates a range of possible solutions using sketches with explanatory notes.	Remember (procedure), when did we do (procedure)? How do we do (procedure)? What was that (procedure) we did? It was like (procedure).
<b>Prior experiences</b>	Instances where the participant recalls or remembers a prior experience with tools, materials, mechanisms, artefacts and places.	It was like (prior experience) When I saw (prior experience). We did this (prior experience). It should be like (prior experience). I remember when (prior experience) they did (prior experience). How did we do (prior experience)? They said (prior experience).

### **Internal source: design task**

The second internal source that I coded entailed the design task in which the problem statement and instructions were stated. Although the source itself is externally represented, I classified the content and understanding of the problem statement and instructions as an internal source. This is common practice in protocol studies (Eastman, 2001), and the design task is considered to be internal to the design task environment. However, I did not consider the pictures in the design task to be part of the internal information. I included pictorial information as material scaffolds for the participants since they did not have access to information about the problem context. Table 3.6 presents a description of the sources that I coded from the design task, and the key words that I looked for in the verbal protocol to interpret the sources of information.

**Table 3.6: Indicators for identifying information access and use from design task**

Information source	Description	Words that acted as indicators
<b>Problem statement</b>	A timber company cuts down trees in a forest and uses trucks to transport the logs to a nearby sawmill. It takes very long for workers to manually load the logs onto a truck one by one. The company needs a machine that can pick up logs from the ground and transfer them onto a truck quickly and safely (Johnstone et al., 2013).	Trucks, transport, workers, manual, load logs, truck, one log at a time, quickly, fast, safety.
<b>Instructions</b>	Design a model of a machine that can pick up logs from the ground and transfer them onto the transport truck. Consider the environment in which the machine must function. Think about the movements your machine will need to perform. Suggest at least two possible designs that will be able to transfer logs from the ground onto a truck.	Environment in which the machine will operate, will the machine stay in the same position? How high must it lift the logs? Could the machine topple over?, Will the machine make work quicker and faster? Pick up and hold the logs, lift the logs, different movements of the machine, control movements of the machine.

### External source: pictorial information

The first external sources of information that I coded entailed pictorial information that was presented to the participants as supplementary reference material. Therefore, I only coded pictorial information that was not made by the participants themselves. The reason for giving the pictorial information to the participants was to establish the basic role that embodiment plays during the participants' design processes. I therefore looked for instances where the participants accessed and used the pictorial information. I was able to interpret these instances when the participants perceived a picture and spoke about a basic visual element<sup>9</sup>. By coding the pictorial information that the participants accessed and used, I was able to determine when the participants accessed and used pictures during their design processes. I was also able to see how the participants identified basic visual elements in pictures to improve my understanding of Embodiment Theory during the design processes. Table 3.7 summarises a description of the pictures as an information source and key words that I identified in the verbal protocol to code the participants' access and use of pictorial information.

**Table 3.7: Indicators for identifying information access and use of pictures**

Information source	Description	Words that acted as indicators
<b>Pictures</b>	<p>Reference material included additional to the design task. These pictures included Figures 1 – 26 in in the design task. (see Appendix A).</p> <p>Any pictorial media that was not created by the participants themselves, representing information which was useful in their design tasks.</p>	<p>Dependent on watching the video recording to see when participants pointed at, gazed at, read or gestured towards the pictorial information.</p> <p>Utterances, which revealed any of these visual elements (Gibson, 1982):</p> <ul style="list-style-type: none"> <li>• Shape (square, cylinder, rectangle, triangular),</li> <li>• Size (big, small, large, tiny),</li> <li>• Colour (red, green, yellow),</li> <li>• Texture (rough, smooth),</li> <li>• Line (straight lines, curvy lines),</li> <li>• Proportion (higher than, lower than, bigger than),</li> <li>• Weight (thick, thin),</li> <li>• Position (from here, to there, far from there),</li> <li>• Motion (moving, downward, upward),</li> <li>• Surface layout (slant, edges, curvature, corners, faces),</li> <li>• Substance (solid, liquid, viscous),</li> <li>• Lighting (darker, lighter, dim, bright).</li> </ul>

### External source: participants' workbooks

The second external information source that I coded entailed the information contained in the participants' technology workbooks, which I captured on the video recordings. This means that I did not analyse their workbooks, but only the information that the participants accessed and used from their workbooks. As mentioned in Section 3.6.2, I instructed the participants to bring their technology workbooks to the TAPS session, as they might provide extra reference material during their design tasks. I looked for instances on the video recordings in which the participants read, looked at, pointed at or gestured towards their workbooks. This enabled me to code the verbal utterances

<sup>9</sup> Shape, size, colour, texture, line, proportion, weight, position, motion, surface layout, substance and lighting (Gibson, 1982).

during those same instances. In Table 3.8, I give a description of the workbook as an information source, and subsequent keywords that I interpreted from the verbal protocols.

**Table 3.8: Indicators for identifying information access and use from the participants' workbooks**

Information source	Description	Words that acted as indicators
<b>Workbook</b>	<p><i>Accessing and using information contained in their workbook. This might include textual or pictorial information.</i></p> <p><i>Reading information about mechanisms from their workbook.</i></p>	<p><i>Dependent on watching the video recording to see when participants pointed at, gazed at, read or gestured towards the workbooks.</i></p> <p><i>Let's look in our books, here it says, which page are you on?, where are you reading?</i></p> <p><i>Reading verbatim information from their workbooks.</i></p> <p><i>Utterances, which revealed any of these visual elements (Gibson, 1982):</i></p> <ul style="list-style-type: none"> <li>• <i>Shape (square, cylinder, rectangle, triangular),</i></li> <li>• <i>Size (big, small, large, tiny),</i></li> <li>• <i>Colour (red, green, yellow),</i></li> <li>• <i>Texture (rough, smooth),</i></li> <li>• <i>Line (straight lines, curvy lines),</i></li> <li>• <i>Proportion (higher than, lower than, bigger than),</i></li> <li>• <i>Weight (thick, thin),</i></li> <li>• <i>Position (from here, to there, far from there),</i></li> <li>• <i>Motion (moving, downward, upward),</i></li> <li>• <i>Surface layout (slant, edges, curvature, corners, faces),</i></li> <li>• <i>Substance (solid, liquid, viscous),</i></li> <li>• <i>Lighting (darker, lighter, dim, bright).</i></li> </ul>

#### **External source: 3D models**

The third external information source that I coded entailed the participants' interaction with physical objects in their technology learning environment. As mentioned in Section 3.6.2, I gave the participants a collection of basic stationery items and a model of a Lego fishing rod. I looked for instances on the video recordings in which the participants interacted with physical objects. This enabled me to code the verbal utterances during those same instances. In Table 3.9, I give a description of the 3D modelling as an information source, and subsequent keywords that I interpreted from the verbal protocols.

**Table 3.9: Indicators for identifying information access and use of 3D models**

Information source	Description	Words that acted as indicators
<b>3D Model</b>	<i>Physical 3D objects in the extended design task environment with which the participants interacted. Included basic stationery items and a Lego model of a fishing rod.</i>	<p><i>Dependent on watching the video recording to see when participants pointed at, gazed at, or gestured towards the physical objects.</i></p> <p><i>Utterances, which revealed any of these visual elements (Gibson, 1982):</i></p> <ul style="list-style-type: none"> <li>• <i>Shape (square, cylinder, rectangle, triangular),</i></li> <li>• <i>Size (big, small, large, tiny),</i></li> <li>• <i>Colour (red, green, yellow),</i></li> <li>• <i>Texture (rough, smooth),</i></li> <li>• <i>Line (straight lines, curvy lines),</i></li> <li>• <i>Proportion (higher than, lower than, bigger than),</i></li> <li>• <i>Weight (thick, thin),</i></li> <li>• <i>Position (from here, to there, far from there),</i></li> <li>• <i>Motion (moving, downward, upward),</i></li> <li>• <i>Surface layout (slant, edges, curvature, corners, faces),</i></li> <li>• <i>Substance (solid, liquid, viscous),</i></li> <li>• <i>Lighting (darker, lighter, dim, bright).</i></li> </ul>

**External source: participants' sketches**

The fourth information source that I coded entailed the participants' interaction with their sketches. It is assumed that once a sketch has been produced, the representation itself becomes an external object that can be reused and reinterpreted (Haupt, 2013; Goel, 2001; Hope, 2005). Therefore, I used the video recording to look for instances of sketching activity as well as instances in which the participants pointed to, gestured towards or interacted with a previously drawn sketch. As a result, I was able to identify the verbal utterances made at the same time, and code the verbal utterances that were made during the sketching activity or the interaction with previous sketches. In Table 3.10, I give a description of the sketches as an information source, and subsequent keywords that I interpreted from the verbal protocols.

**Table 3.10: Indicators for identifying information access and use of sketches**

Information source	Description	Words that acted as indicators
Sketches	<p>Sketches which the participants made to represent their understanding of the design problem, or potential design ideas.</p> <p>Sketches also represented the process of developing proposed ideas.</p>	<p>Dependent on watching the video recording to see when the participants sketched, pointed at, gazed at, or gestured towards the sketches.</p> <p>Utterances, which revealed any of these visual elements (Gibson, 1982):</p> <ul style="list-style-type: none"> <li>• Shape (square, cylinder, rectangle, triangular),</li> <li>• Size (big, small, large, tiny),</li> <li>• Colour (red, green, yellow),</li> <li>• Texture (rough, smooth),</li> <li>• Line (straight lines, curvy lines),</li> <li>• Proportion (higher than, lower than, bigger than),</li> <li>• Weight (thick, thin),</li> <li>• Position (from here, to there, far from there),</li> <li>• Motion (moving, downward, upward),</li> <li>• Surface layout (slant, edges, curvature, corners, faces),</li> <li>• Substance (solid, liquid, viscous),</li> <li>• Lighting (darker, lighter, dim, bright).</li> </ul>

By coding the information sources that the participants accessed and used, I was able to understand what information sources they were talking about that contributed to the content of their thoughts, identified in Level 2 of the coding scheme (Figure 3.4). In addition to this, I was able to understand which information sources the participants were more or less likely to use during their design processes. This contributed to addressing my first research question, namely, “*What information sources do learners access and use during the early phases of the design process?*”

I coded both internal and external information sources in order to establish elements from my conceptual framework; coding the information sources that the participants accessed and used therefore contributed to the methodological strength of this study. However, I still needed to understand how the participants accessed and used these information sources. I therefore identified mental operators in Level four.

**Level four** entailed coding the mental operators that the participants applied to the content that they accessed from information sources in order to facilitate a transformation. Transforming information helps designers to enhance their understanding of the information. Therefore, designers use operators<sup>10</sup> to identify missing information in the ill-structured design task (Goel, 1995). This implied that I should code instances in which the participants asked questions, perceived information, or recalled information by evaluating, elaborating, proposing, modifying, justifying, reading, qualifying, requesting, repeating or commenting on information that they had paid attention to from Level 3.

<sup>10</sup> For example, designers might transform their understanding of a design context by elaborating on user needs. As the designers elaborate, new information becomes available which was not previously in the extended design task environment.

I interpreted transformation of information to imply a transformation of understanding of the design problem and possible solutions, which resulted in progression from attempting to understand the design problem to finding and generating solutions to the problem. Each transformation made by the participants was the outcome of an operator, which was applied to content (Level 2) that originated from a source of information (Level 3). This means that I considered a transformation as the outcome of an operator that was applied to information from a specific source.

In Table 3.11, I provide a description of the operators that I derived from Goel (2013) to code and interpret the transformations present in the participants' verbal protocols. I coded verbal utterances and focused on specific content (Level 2) to which an operator was applied.

**Table 3.11: Indicators for identifying when operators were applied**

Operators	Indicators
<b>Propose</b>	Suggesting new information with some level of commitment.
<b>Evaluate</b>	Evaluating information sources or external representation, based on specific criteria.
<b>Comment</b>	Reporting on an activity and not the execution thereof. Generally involves participants' explanations of what they have done, or general remarks which are not task relevant.
<b>Modify</b>	Modification of a component or existing idea, which has already been proposed.
<b>Elaborate</b>	Elaboration of existing component or idea by suggesting new information.
<b>Justify</b>	Justification of operations, which involves proposing, modifying of, or elaborating on existing components or ideas.
<b>Read</b>	Involves the participants' reading of any material in the task environment such as the design task, workbooks, or external sources of information.
<b>Qualify</b>	Statements used to hedge or further qualify existing components or ideas.
<b>Request</b>	Any request made by participants to me in asking questions or making suggestions.
<b>Repeat</b>	The application of the same operator to the same content.
<b>Misc.</b>	Any utterance which could not be coded with the above-mentioned operators.

By coding the mental operations with which the participants transformed accessed information sources, I was able to identify how information sources were accessed and used. In this way, I was able to determine the purpose for which they had been used, i.e. problem structuring or solving (Level 5). Therefore, I needed to code and interpret the operators that the participants applied in order to identify how they used information to transform their understanding of the design problem.

**Level five** entailed coding and interpreting the distinct cognitive phases in the design problem solving space and included problem structuring and solving (Goel 1995). Problem structuring referred to utterances that were focused on finding missing information about the design objectives, people and context of the design problem (Level 2). Problem solving referred to utterances that focused on finding and generating ideas about possible solutions, as well as the development of design ideas (Level 2).

In order to code the cognitive phases of the participants, I had to identify the operations (Level 4) on content (Level 2) to produce transformations. By doing so, I was able to identify the purpose of each transformation in the type of cognitive activity that followed. Tables 3.12 – 3.14 summarise how I used the content in conjunction with operators to identify problem structuring, problem solving and Leaky phase transformation.

**Table 3.12 : Indicators for coding and interpreting problem structuring transformations**

Problem structuring					
<i>Utterances based on finding missing information about the people involved, the design objectives, or the problem context</i>					
Content (Level 2)	+	Operator (Level 4)	+	Information Access (Level 3)	= Problem structuring transformations (Level 5)
People; Context; Design objectives.		Read; Evaluate; Justify; Propose; Elaborate.		Recall; Recognition; Questioning; Talking; Writing; Sketching; 3D modelling; Perception-Action.	<ul style="list-style-type: none"> <li>• Read/evaluate information from the design task;</li> <li>• Evaluate the problem/context;</li> <li>• Propose design objective;</li> <li>• Evaluate/elaborate information about the design objective;</li> <li>• Propose/justify a design requirement;</li> <li>• Propose/justify a design constraint;</li> <li>• Evaluate/elaborate resources available in the environment;</li> <li>• Elaborate on context;</li> <li>• Propose environmental constraints.</li> </ul>

By paying attention to the content of the participants' thoughts (Level 2) on how they accessed the information source (Level 3), and the operator that they applied to the content (Level 4), I was able to code and interpret the problem structuring transformation that took place. I assumed that problem structuring transformations were the result of finding missing information about the people involved, the context of the problem, and the design objectives that the participants wanted to address (Goel et al., 2013).

**Table 3.13: Indicators for coding and interpreting problem solving transformations**

Problem solving					
<i>Utterances based on finding missing information about possible design solutions, or development of a design solution</i>					
Content (Level 2)	+	Operator (Level 4)	+	Information Access (Level 3)	= Problem solving transformations (Level 5)
Function;		Read;		Recall;	• Evaluating existing solutions;
Behaviour;		Evaluate;		Recognition;	• Proposing design limitations;
Structure.		Justify;		Questioning;	• Modifying existing solutions;
		Propose;		Talking;	• Proposing/evaluating a design idea;
		Elaborate;		Writing;	• Elaborating on a design idea;
		Modify;		Sketching;	• Justifying ideas;
		Qualify.		3D Modelling;	• Qualifying ideas;
				Perception-Action.	• Modifying earlier ideas.

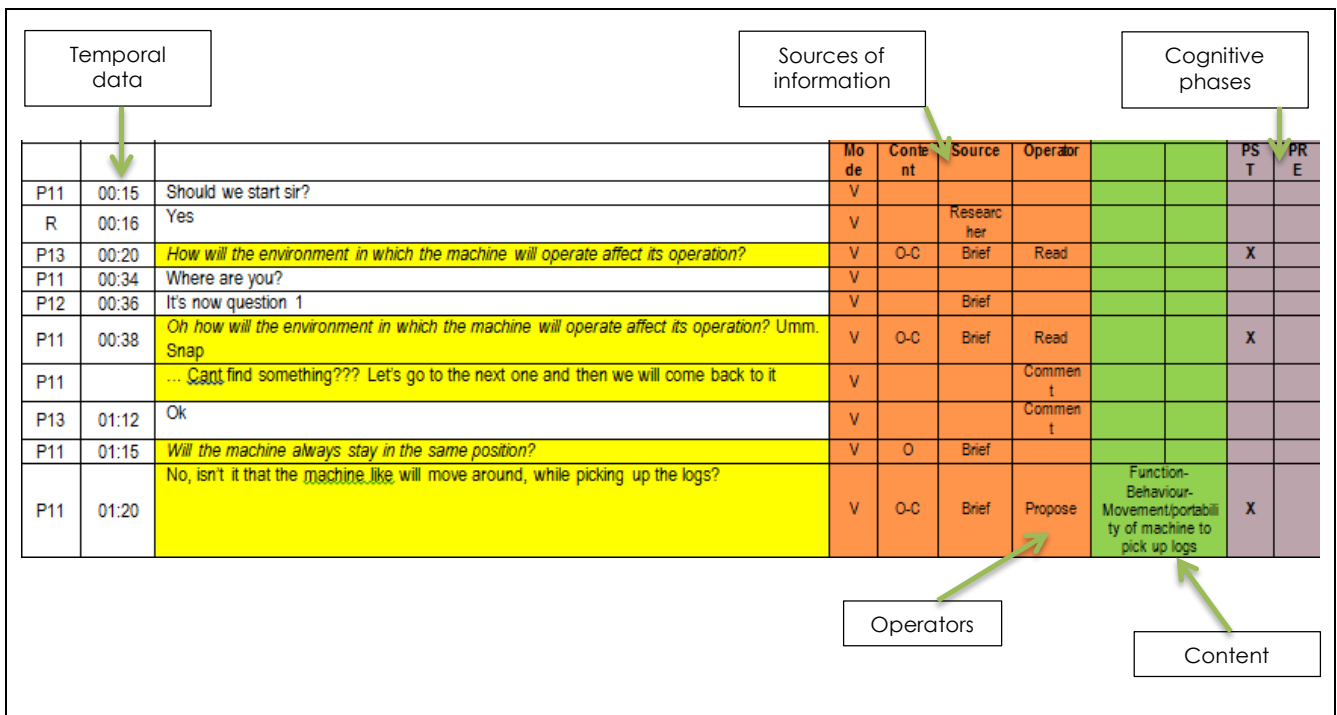
By paying attention to the content of the participants' thoughts (Level 2), how they accessed the information source (Level 3), and what operator they applied to the content (Level 4), I was able to code and interpret the problem solving transformation that took place. I assumed that problem solving transformations were the result of finding missing information about possible design ideas that the participants generated, or had chosen in order to establish a function, behaviour and structure for the design idea (Goel et al., 2013).

**Table 3.14: Indicators for coding and interpreting Leaky phases**

Leaky phases					
<i>Utterances based on finding missing information about possible design solutions, or development of a design solution, while simultaneously searching for missing information about the people involved, the design objectives, or the problem context</i>					
Content (Level 2)	+	Operator (Level 4)	+	Information Access (Level 3)	= Leaky phase transformations (Level 5)
Function;		Read;		Recall;	• Evaluating existing solutions based on proposed; design objective/needs of people involved
Behaviour;		Evaluate;		Recognition;	• Proposing design limitations, based on environmental constraints/design objectives;
Structure;		Justify;		Questioning;	• Justifying ideas, based on design objectives/context;
People;		Propose;		Talking;	• Elaborating on a design idea;
Context;		Elaborate;		Writing;	• Modifying existing solutions based on environmental constraints;
Design objectives.		Modify;		Sketching;	• Modifying earlier idea/based on needs of people;
		Qualify.		3D Modelling;	• Qualifying idea to address design objective/environmental constraints.
				Perception-Action.	

By paying attention to the content of the participants' thoughts (Level 2), how they accessed the information source (Level 3), and what operator they applied to the content (Level 4), I was able to code and interpret the Leaky phase transformation that took place. I assumed that Leaky phase transformations were the result of finding missing information about the function, behaviour or structure of possible or chosen design solutions while considering the people involved, the context of the problem, and the design objectives that the participants wanted to address (Goel et al., 2013).

Figure 3.4 indicates how I structured and coded the verbal data for this study manually. I primarily used Microsoft Excel in order to code each level of the data-structuring plan (Figure 3.3).



Temporal data			Sources of information			Cognitive phases					
			Mode	Content	Source	Operator		PS	T	PR	E
P11	00:15	Should we start sir?	V								
R	00:16	Yes	V		Researcher						
P13	00:20	How will the environment in which the machine will operate affect its operation?	V	O-C	Brief	Read				X	
P11	00:34	Where are you?	V								
P12	00:36	It's now question 1	V		Brief						
P11	00:38	Oh how will the environment in which the machine will operate affect its operation? Umm. Snap	V	O-C	Brief	Read				X	
P11		... Cant find something??? Let's go to the next one and then we will come back to it	V			Comment					
P13	01:12	Ok	V			Comment					
P11	01:15	Will the machine always stay in the same position?	V	O	Brief						
P11	01:20	No, isn't it that the machine like will move around, while picking up the logs?	V	O-C	Brief	Propose	Function-Behaviour-Movement/portability of machine to pick up logs			X	

Figure 3.5: Qualitative data structuring implementation

By coding the cognitive phases of the participants, I was able to indicate the purpose of each transformation, which I identified in Level four. In so doing, I was able to address my second and third sub-research questions, namely, 'How do learners access and use internal and external sources of information when structuring design problems?' and "How do learners access and use internal and external sources of information when solving design problems?'

### 3.7.2 Quantitative data structuring

I transcribed the verbal data into textual data, and transferred the text to a quantitative data sheet where each verbal utterance was classified according to the moment in time when it was instantiated. As a result, I was able to study sequences of thoughts on the basis of the structure that the temporal data provided me.

Furthermore, I was able to generate quantitative data from my qualitative coding. Once I had coded the cognitive phases (Level 5), operators (Level 4) and the information sources (Level 3), I was able to count the instances where the participants accessed and used information sources, and the cognitive phases that the participants exhibited. In that way, I was able to determine the frequency and distribution of information sources and cognitive phases throughout the participants' design processes. This enabled me to address my first sub-research question, namely, *“What information sources do learners access and use during the early phases of the design process?”*

### 3.8 Quality assurance

I ensured the quality of this study by following the quality assurance measures provided by Babbie and Mouton (2006), in conjunction with measures for quality assurance, as postulated by Yin (2014) specifically for case study research designs. These two sources served to imbue the study with the necessary rigour to generate trustworthy, valid and reliable findings. Together with an alignment with my pragmatist research paradigm, these quality measures contributed to the usefulness of the guidelines generated by this study.

#### 3.8.1 Trustworthiness

In order to ensure the trustworthiness of the findings, I subscribed to four measures of trustworthiness, namely, credibility, transferability and confirmability, and dependability as described by Babbie and Mouton (2006). These four measures of trustworthiness are discussed in the next section.

The notion of trustworthiness as described by Lincoln and Guba (1985) relates to a researcher's ability to persuade their audience that the findings of a study are worth paying attention to (Babbie & Mouton, 2006). Four measures of trustworthiness, described by Lincoln and Guba (1985), that this study subscribed to are mentioned in Table 3.15, and discussed further below.

**Table 3.15: Measures of trustworthiness (Babbie & Mouton, 2006, pp. 276-278)**

<b>Credibility</b>	Ensuring compatibility between constructed realities in participants' minds, and those that are attributed to them.
<b>Transferability</b>	Ensuring that findings can be applied in different contexts or with different participants.
<b>Confirmability</b>	Ensuring that findings are the product of the focus in the study, and not based on the biases of the researcher.
<b>Dependability</b>	Ensuring that findings are consistent and can be repeated.

For this study, credibility relates to the certainty of the truth of my findings (Lincoln & Guba, 1985). This implied that I approached the credibility of this study by ensuring that there was compatibility between how each group of participants engaged in their design processes and the interpretation thereof. I took several measures to ensure the credibility of this study. Firstly, I enhanced the credibility by persistently engaging in observations of the verbal utterances captured by the video

recordings during data analysis. The credibility of the inferences that I made about the cognitive phases and information access and use of the participants was directly dependent on meticulous re-examination of the verbal utterances, while constantly testing interpretations in terms of the conceptual framework of this study (Ericsson & Simon, 1993). Capturing each group of participants' design processes on video recordings also allowed me to repeatedly watch these recordings to ascertain the context of the participants' utterances. Therefore, I was able to credibly analyse verbal data in the context of their occurrence, since verbal data did not show what the participants gazed or pointed at, or what sketches the participants were speaking about. Additionally, the video recordings allowed me to slow down playback in order to accurately transcribe verbal data (Cohen, Manion & Morrison 2011).

Secondly, I enhanced the credibility of my findings by means of prolonged engagement in technology classrooms prior to this study. I was hence able to observe how technology learners engaged in design tasks in order to adequately conceptualise my data collection methodology. I also engaged with the literature on the theoretical underpinnings of design cognition theories, and formed an understanding of how design cognition has been empirically studied in expert and novice disciplines.

Thirdly, I also subscribed to pragmatic assumptions by collecting multiple data types to address my research questions (see Section 3.2), which I could triangulate to enhance the credibility of the findings (Creswell, 2014). Cohen et al. (2011) explain that triangulation involves a researcher's attempt to increase the richness of findings by studying data from more than one viewpoint. During my data collection, discussed in Section 3.6, I was able to collect three data types: verbal, visual and temporal, which were necessitated by my conceptual framework. I could analyse each group of participants' information access and usage activities in terms of the Information Processing Theory and the Embodiment Theory by drawing from verbal, visual and temporal data types. Therefore, I was able to enrich my findings by describing each group of participants' cognitive actions from three data types. Moreover, I could also enhance the credibility of my own interpretations by cross-referencing between data types. This means that I continuously made interpretations based on my observations of verbal, visual and temporal data types.

For my study, I regarded transferability as the applicability of findings to other contexts (Lincoln & Guba, 1985; Babbie & Mouton, 2006). In order to enhance the transferability in this study, I collected a thick description of the research context, and used purposive sampling techniques (Guba & Lincoln, 2005), described in Section 3.5. Throughout the data analysis, I aimed to understand the authentic world, i.e. the technology extended design task environment of each group of participants.

I hence organised utterances made by participants according to this study's conceptual framework. I therefore collected sufficient information about the context of the research participants to allow readers to make their own judgments about the findings of this study. In addition to this, by incorporating purposive sampling techniques, I was able to maximise the range of specific information that I could obtain from the research context.

In this study, I considered confirmability to denote the degree of neutrality with which I approached the data analysis (Lincoln & Guba, 1985; Babbie & Mouton, 2006). I contributed to the confirmability of the findings by providing an audit trail, i.e. an adequate confirmability trail that should be left to enable the examiner to determine if the conclusions, interpretations, and recommendations could be traced back to their sources. Leaving an audit trail meant that I had to provide evidence of data collected during the inquiry. These data sources include (Babbie & Mouton, 2006):

- *Raw data*: Recorded protocols and external representations;
- *Data reduction and analysis products*: coding schemes;
- *Data synthesis and reconstruction products*: themes that were developed during the empirical investigation, findings and conclusions in the final dissertation; and
- *Data collection instrument*: The design task that was given to learners to initiate design cognition behaviour.

I regarded the dependability of my study as relying on the extent to which I could show that my findings are consistent and repeatable (Lincoln & Guba, 1985; Babbie & Mouton, 2006). I decided to video record the design processes of each group of participants in order to establish a high degree of reliability when coding verbal data in terms of the participants' cognitive phases and information access and use. In order to achieve this, I utilised an inter-coder reliability technique, i.e. a reliability technique in which corresponding codes can be found by two different coders in the same data set (Van Someren et al., 1994). Therefore, I enhanced the credibility of this study by asking another researcher<sup>11</sup> in design cognition to independently classify a sample of ten examples of verbal utterances according to early phases of the design process and information access and use in accordance with the conceptual framework of this study. The consistency of the agreement between me and the rater was determined by using the following formula (Jackson, 2006, p. 61):

$$\begin{aligned}\text{Inter-rater reliability} &= \frac{\text{Number of agreements}}{\text{Number of possible agreements}} \times 100 \\ &= \frac{9}{10} \\ &= 90\%\end{aligned}$$

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<sup>11</sup> During this stage of the research process, I approached a researcher who was studying the early phases of novice industrial designers' design processes. He was therefore familiar with my theoretical and conceptual framework.

A review of the rater's classification revealed that the small disagreement noted above (10%) could be attributed to the fact that cognitive phases during the early phases are not always clearly distinguishable (Restrepo & Christiaans, 2004; Goel, 1995). Stemler (2004) suggests that values ranging from 75% to 100% demonstrate a satisfactory level of credibility when determining inter-rater reliability based on the percentage of absolute agreement. Establishing an agreement between two sets of codings embedded in the conceptual framework of this study seemed to have resulted in credible inferences.

### **3.8.2 Validity and reliability**

In order to ensure the reliability and validity of the findings for this study, I subscribed to the guidelines for case study research designs, as mentioned by Yin (2014), including construct validity, internal validity, external validity, and reliability. These measures for validity and reliability in the context of case studies are discussed in the next section.

For this study, construct validity meant the identification of correct operational measures to study constructs (Yin, 2014). I was able to enhance the construct validity by rigorously referring to my conceptual framework while making interpretations of the data. More specifically, I studied the assumptions underlying the Information Processing and Embodiment Theory in order to delineate the relationships between how cognitive actions emerge as a result of internal and external information access and usage activities, during each group of participants' design processes. I was therefore able to enhance the construct validity by ensuring that internal and external sources were continually linked to the external representations that the participants made during their design processes. Following a TAPS methodology allowed me to describe the moment to moment interactions of participants with internal and external sources of information, resulting in a description of the relationship between participants and information sources. Although I did not have access to the learners' internal sources of information, the Information Processing Theory combined with the TAPS methodology allowed me to assume that the external representations of the participants were linked to their working memory (Van Someren et al., 1994).

Yin (2014) defines internal validity as the identification of causal relationships among variables. I specifically emphasised the causal relationships between information sources and the cognitive phases exhibited by each group of participants. In order to ensure internal validity, I emphasised the transformation of participants' understanding of the design problem and possible solutions by sequentially identifying access and use of information sources. By emphasising the sequential development of external representations, including participants' talking, sketching, 3D modelling, and writing, I repeatedly described how the interaction between the participants and sources of information causally generated new information in their external representations, which contributed to their transformation of understanding.

The Extended Cognition Theory allowed me to consider both internal and external sources of information, while the TAPS methodology allowed me to identify and describe how these sources of information surfaced in the participants' external representations.

External validity refers to the definition of a field of study in which the findings can be generalised (Yin, 2014). As part of the preparation for this study, I reviewed methodological choices against the literature on both novice and expert design cognition studies. Additionally, I consulted with an expert colleague in design cognition studies. However, few studies in design research and TE focus on the contribution of sources of information during the design process from a psychological viewpoint (Petrina, 2010; Middleton, 2010; Zuga, 2004). Therefore, I continuously referred back to the Extended Cognition Theory in order to contribute to the developing field of cognition in TE. It should be noted that the aim of this study was not to generalise findings to other populations. Instead, I wanted to investigate and describe the extended cognition of Grade 9 participants during a design task in order to formulate practical guidelines for the effective facilitation of the early phases of the design process.

Reliability with regard to case study research design means that the data collection for this study can be repeated (Yin, 2014). To this end, I utilised a TAPS methodology in which a specific protocol was followed in order to collect data. Since the case study design that I used for this study depended heavily on the context in which the TAPS was conducted, I collected rich descriptions of the research context. I also provide an audit trail, which was discussed in Section 3.8.1.

### **3.9 Ethical considerations**

On account of the age ( $\pm 14-16$ ) of the participants in this study, I sought permission from various authorities in order to ensure that research was conducted in an ethical manner. Firstly, I sought permission to conduct research from the Ethics Committee of the University of Pretoria's Faculty of Education. Secondly, permission to conduct research in a public school was sought from the Department of Basic Education's (DoBE) provincial district office. One constraint imposed by the DoBE in conducting research in a public school was that research could not be conducted during normal technology tuition hours. Therefore, the research was conducted after the participants had finished with school, during extra class hours. Care was taken to create a naturalistic learning environment in which the participants could engage in information access and usage activities.

Thirdly, I sought permission from the principal and School Governing Body in whose school the research was to be conducted. Fourthly, permission was sought from the teacher in whose classes I video recorded the design tasks. Fifthly, permission letters were sent to the parents of the learners participating in the research study. Finally, informed assent letters were given to the learners participating in the study.

During the process of asking permission, I explicitly stated that participation in the research study was entirely voluntary and participants had the opportunity to withdraw from the research study at any stage. All authorities received letters in which the aims and procedures of the study were explained. In addition to these, I emphasised the rights of the participants by explaining the following ethical principles in the informed assent letters (Babbie & Mouton, 2006; Cohen et al. 2011):

- *Voluntary participation* in the research study: participants could withdraw from the study at any time without any negative consequences;
- *Safety during participation* in the research study: the participants were not placed in any situation where they could have been hurt – physically or emotionally. I also ensured that participants were comfortable during the TAPS process by providing them with the chance to explore the TAPS environment and ask questions.
- *Participants' privacy* was respected by means of confidentiality and anonymity by omitting their real names and using codes such as P2 for referencing their particular cognitive actions during the design task in the verbal and visual data.
- *Trust during the research study*: participants were not subjected to any acts of deception or betrayal in the research procedures or published outcomes.
- *Informed consent* (parents and teachers) and assent (participants) forms were attached to the permission letters in which the relevant authorities had to acknowledge their participation in the study by signing the letters before research commenced.

The raw data that I collected during the TAPS process will also be stored in a locked designation at the University of Pretoria. This way, the identities of the participants should be protected. I have also included copies of my coding transcripts and the sketches made by the participants for the external examiner in order to provide a transparent audit trail. In this way, the external examiner can judge the neutrality and honesty that this study was conducted with.

### 3.10 Conclusion

Chapter 3 focused on a detailed description of the research methodology that I planned and implemented. I started Chapter 3 by explicating my research paradigm and the research approach that I followed. Thereafter, I situated my study as a case study research design within the bounds of a technology learning environment. Grade 9 technology learners were subsequently discussed as the target population for this study, followed by a thick description of their background context and the sampling methods that I used to select participants. I then described the manner in which I utilised the TAPS methodology to collect verbal, visual and temporal data. I concluded the chapter by describing my data analysis and interpretation procedures, as well as the quality assurance measures and ethical considerations that I adhered to in the planning and implementation of this study.

## Chapter 4 : Data analysis and discussion

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### 4.1 Chapter overview

The purpose of Chapter 4 is to discuss the data analysis and findings of this study. This discussion presents a description of the participants' cognitive processes from an Extended Cognition viewpoint. As discussed in Chapter 3, Section 3.6, I gave three groups of participants a design task to complete in a naturalistic technology learning environment. In particular, I analytically investigated the design problem solving space of Grade 9 technology participants in terms of the two distinct cognitive phases, namely, problem structuring and solving. I was interested in which information sources the participants used and how they used them to solve their design problem by designing a mechanical lifting machine. This chapter reports on the data analysis and interpretation, which I applied to address the primary research question of this study, namely:

#### **How do internal and external sources of information contribute to the development of Grade 9 learners' design cognition during the early phases of the design process?**

In order to address the primary research question, I formulated three sub-questions:

1. *What information sources do learners access and use during the early phases of the design process?*
2. *How do learners access and use internal and external information sources when structuring design problems?*
3. *How do learners access and use internal and external information sources when solving design problems?*

### 4.2 Contextualising the design process

For data collection purposes, I prepared exactly the same design task for each group of participants to engage them in a design process (see Appendix A). This also served as an internal reliability measure, ensuring that all groups of participants were provided with the same input information at the start of their design process. The context for the design problem was a logging environment, where a timber company required a machine to lift logs from the ground onto a transport truck. The timber company's need for a machine was based on current manual log-loading practices, which are time consuming. The design problem therefore required each group of participants to:

*"Design a model of a machine that can pick up logs from the ground and transfer them onto the transport truck. You only have to design the lifting machine, not the truck".*

Their designed machine needed to replace manual work by making work easier and faster. The design task that I provided, implied that the participants should design a model of a machine that could replace manual work. I also gave each group of participants instructions that yielded information about the design considerations and requirements. However, this information was purposefully insufficient in order to elicit problem structuring activities from the participants. Instead of providing explicit information about the design problem, I constructed open-ended questions to stimulate their search for missing information. I provided these questions to the participants in their instructions:

1. Consider the environment in which the machine must function. Discuss the following questions: (15 minutes)
  - How will the environment in which the machine will operate affect its operation?
  - Will the machine always stay in the same position?
  - How high will it have to lift the logs?
  - How will you ensure that the machine will not topple over?
  - How will the machine make the work faster?
2. Think about the movements your machine will need to perform. Which mechanisms can you use to: (20 minutes)
  - Pick up and hold the logs?
  - Lift the logs?
  - Create different movement in different parts of the machine?
  - Control the movements of the machine?
  - Move the machine around, if necessary?
3. Suggest at least two possible designs that will be able to transfer logs from the ground onto a truck. (25 minutes)

In the following sections (4.3.1 – 4.3.3), I describe three emerging patterns that I derived from investigating the quantitative data. In Section 4.3.1, I identify which cognitive phases the participants exhibited during the early phases of the design process. In Section 4.3.2, I establish the internal and external sources that the participants accessed and used during their design processes. Finally, in Section 4.3.3, I indicate what sources of information each group of participants accessed and used during each of the cognitive phases respectively.

## 4.3 Quantitative data analysis

### 4.3.1 Frequency of the distinct cognitive phases

The purpose of this section is to contextualise the cognitive phases that each group of participants exhibited during their design processes. I counted instances of problem structuring and solving based on my interpretation of the content of the participants' thoughts, the information that was accessed, and the operator that was applied (see data structuring in Section 3.7). In so doing, I was able to quantify the instances and distribution of each cognitive phase across all participants' design processes. Table 4.1 indicates that the participants in all three groups engaged predominantly in problem solving compared to problem structuring during their design processes. Furthermore, the table shows that problem structuring and Leaky phases occurred roughly the same amount of times.

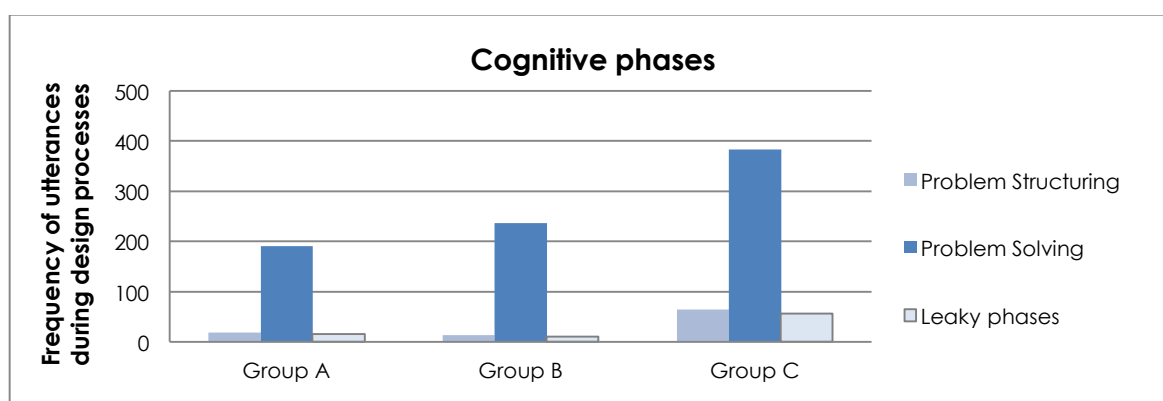
**Table 4.1: Frequency and percentage of utterances in each cognitive phase made by the groups of participants**

		Frequency	Total utterances	Percentage
Group A	Problem structuring	19	338	5.6
	Problem solving	191		56.5
	Leaky phases	16		4.7
Group B	Problem structuring	14	360	3.9
	Problem solving	237		65.8
	Leaky phases	11		3.1
Group C	Problem structuring	65	577	11.3
	Problem solving	384		66.6
	Leaky phases	57		9.9

The first pattern emerging from the descriptive statistical information in Table 4.1 indicates that problem structuring utterances occurred less than 15% during each group's design process. More than 50% of the utterances focused on problem solving, indicating that the majority of the participants' design processes were dominated by design problem solving activities. Findings in design cognition suggest that experts spend the majority of their time focusing on design solutions rather than design problems, whereas novice designers tend to focus on the design problem (Lawson, 2005; Lawson & Dorst, 2009). Therefore, the findings of this study seem to be contradictory to the typical design behaviour of novice designers. However, a recent large-scale study (Kelley, Capobianco & Kaluf, 2014) conducted verbal protocol studies on high school students and found that a majority of the participants spent most of their time brainstorming solutions, whereas less time was spent on defining the design problem.

One possible reason for the dominance of problem solving utterances might also be found in the nature of the solution focused instructions presented in the design task. As discussed in Chapter 3 (Section 3.6), I adapted a design task from a prescribed textbook for Grade 9 technology. The instructions in the design task seemed to focus more on guiding learners to find and explore design solutions rather than understanding the nature of the logging environment, and the users' needs and wants. This was also evident in the lack of pictorial information present in the prescribed textbook about the design context, since it contained only one picture of a truck in the logging environment, and no pictures of the workers involved in lifting logs from the ground to the truck. I therefore adapted the design task by providing all the participants with supplementary pictorial information about the problem context to enhance their problem structuring activities.

Figure 4.1 shows a graphical representation of the frequency of utterances representing each group of participants' cognitive phases.



**Figure 4.1: Frequencies of cognitive phases**

Figure 4.1 shows that Group C had significantly more problem solving utterances than Group A and B. This might be ascribed to the total utterances made by Group C, amounting to 577, which were more than Group A and B's utterances, amounting to 360. Another reason might be the number of information sources that were accessed and used during their design processes, which will be explored in Section 4.3.2.

The second pattern that I found from the quantitative analysis of the participants' cognitive phases was the overlap between the problem structuring and problem solving phases. For this study, I viewed these overlaps of cognitive phases as 'Leaky phases', consistent with expert design cognition (Haupt, 2013) in which an understanding of the solution might trigger thoughts that help to understand the problem, and *vice versa*. As visualised in Table 4.1, the Leaky phases occurred roughly the same amount of times as the problem structuring utterances made by each group of participants. One explanation might be suggested by TE literature (Kimbell & Stables, 2008; De Vries, 2005), which suggests that learners' understanding of their design problem develops simultaneously with their understanding of the design solution. Studies conducted on expert designers reveal that

expert designers typically demonstrate Leaky cognitive phases during a design task (Goel, 1995; Kruger & Cross, 2006, Haupt, 2013). It therefore seems important for technology curriculum developers and teachers to consider recognising and allowing the Leaky cognitive phases of novice designers during their design processes. However, few studies in design cognition reveal empirical findings for Leaky phases. The recommendations for allowing Leaky phases during a design process are discussed further in Chapter 5.

### 4.3.2 Frequency of information source access and use

By analysing and interpreting the data from an Extended Cognition perspective, I was able to identify generic sources of information on which novice designers may draw during the early phases of the design process (Goel & Pirolli, 1992). Goel and Pirolli's (1992) characterisation of expert design task environments allowed me to investigate how novice designers access and use sources of information.

In the verbal protocols, I identified the frequency of utterances that were indicative of both internal and external information access and use of the participants. This behaviour is similar to that of expert designers, who also typically access and use internal and external sources of information to structure and solve their design problems (Haupt, 2014). However, the theories for investigating the information access and usage behaviour of novice designers are still lacking in the literature (Petrina, 2010). For this study, I therefore had to draw from empirical findings on expert designers in order to investigate the information access and usage behaviour of Grade 9 technology participants during the early phases of their design processes.

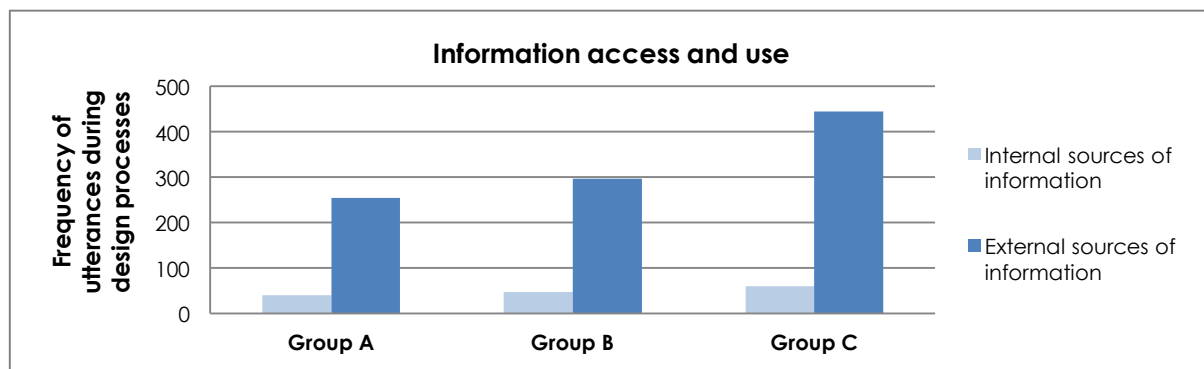
Table 4.2 summarises the frequency and percentage of the information access and use of each group of participants.

**Table 4.2: Frequencies and percentages of information access and use**

		Frequency	Total utterances	Percentage
Group A	Internal sources of information	41	338	12.1
	External sources of information	254		75.1
Group B	Internal sources of information	47	360	13.1
	External sources of information	297		83
Group C	Internal sources of information	60	577	10.4
	External sources of information	445		77.1

In Table 4.2, the frequency of utterances indicating internal information access and use occurred less than 15%, while more than 75% of the utterances from each group demonstrated the participants' external information access and use. Hence, in this study the participants relied predominantly on external sources of information on which they based their design decisions. Kruger and Cross (2006) call this phenomenon information-based design, where expert designers typically

search for information from external sources of information to structure and solve design problems, as opposed to problem-driven design and knowledge-driven design, in which expert designers predominantly rely on previous experience and knowledge to structure and solve design problems. In accordance with this, novice designers lack previous design experience and conceptual knowledge, and do not typically engage in problem-driven and knowledge-driven designing (De Vries, 2005; Dorst & Cross, 2006). The implication of this finding suggests that technology teachers should plan external sources of information in the technology learning environment effectively. Figure 4.2 visually represents the frequency of utterances indicating information access and use.



**Figure 4.2: Frequencies of information access and use**

Figure 4.2 indicates that Group C accessed and used more sources of information than Groups A and B. There might hence be statistically significant correlations between the number of transformations and the number of information sources which were accessed and used, as the number of cognitive phases of Group C was also significantly higher than those of Group A and B. However, this could be investigated in future studies.

In the next two sub-sections (a-b), I describe the internal and external sources that the participants accessed and used respectively. In Section a), I specifically focus on identifying internal sources of information accessed and used during the participants' design processes. In Section b), I describe the external sources that the participants accessed and used during their design processes.

#### **a) Internal information sources**

During the data analysis for my study, I found evidence of several instances where each group of participants accessed and used internal sources of information to structure and solve their design problems. I used the Information Processing Theory of design cognition, focusing on the content of participants' thoughts, to interpret utterances that indicated internal sources of information as the origin of the participants' thoughts.

Table 4.3 indicates the frequency and percentage of utterances indicating internal sources that were accessed and used, compared to the total number of utterances made during the span of the participants' design processes.

**Table 4.3: Frequencies and percentages of utterances indicating internal sources accessed and used**

		Frequency	Total utterances	Percentage
Group A	Design task	26	338	7.7
	Memory	15		4.4
Group B	Design task	21	360	5.8
	Memory	26		7.2
Group C	Design task	33	577	5.7
	Memory	27		4.7

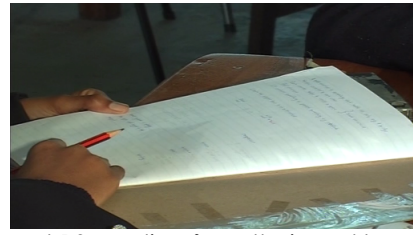
Table 4.3 indicates that all of the participants were able to access and utilise information from their design tasks and memory to structure and solve their design problems. However, in light of Table 4.3, relatively low consideration was given to information stored in the memory during the whole design process. Less than 8% of the design process was spent on accessing and utilising information stored in the participants' memory. This finding suggests that learners do not easily transfer knowledge that was learned during the term into a design process. This finding is consistent with empirical research done on designers, which indicates that novice designers typically do not have the prior experience and knowledge that expert designers have to structure and solve design problems (Cross, 2004; Lawson, 2004).

#### **b) External sources of information**

Integrating the Embodiment Theory with the Information Processing Theory of design problem solving permitted me to observe and report on the external sources of information that the groups of participants accessed and used during the duration of the TAPS process (Haupt, 2014). I considered various situational objects, including pictorial information about the design problem context and existing solutions, participants' workbooks, 3D modelling materials such as stationery items, and sketches that the participants made concurrently during the design task. The design cognition activities which incorporated external sources of information therefore implied an intentional, systemic interactivity between an internal information processor and external information detected in the physical environment (Haupt, 2014; Young, 2004). Photographs 4.1-4.3 capture some of the external information sources that the participants had access to in the extended design task environment. I discussed these external sources of information in Chapter 3, Section 3.6.



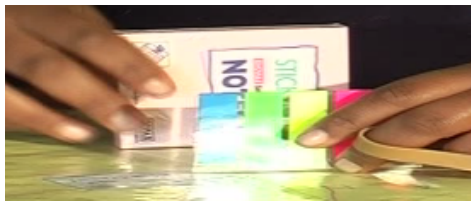
*Participant P13 perceiving pictorial information about the problem context provided in pictorial information to understand how the environment will affect a machine's operation*



*Participant P3 reading from their workbook to find examples of lifting mechanisms*

**Photograph 4.1: External sources Group A accessed**

**Photograph 4.2: External sources Group B accessed**



*Participant P6 using post-it notes, page markers and a rubber band to 3D model a container to help them clarify how logs can be lifted*

**Photograph 4.3: External sources that Group C accessed**

In Photographs 4.1-4.3, I show how I was able to capture instances of external information access and use on the video recordings during the TAPS process. Although I did not analyse the video recordings, I used the video recordings to contextualise the verbal protocols. In so doing, when analysing the verbal protocols I was able to see what each group of participants pointed at, gazed at, interacted with, sketched, modelled and wrote.

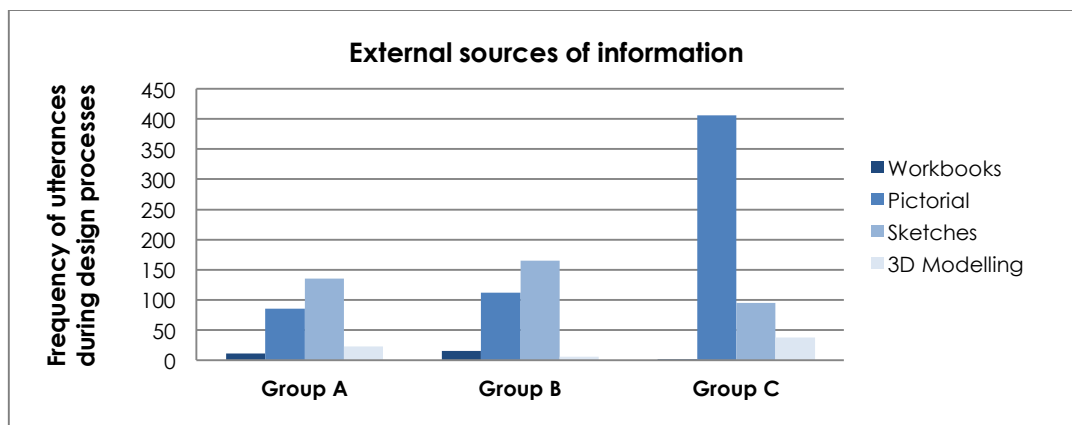
I was able to individuate utterances, which had their origin in external sources of information by identifying how the participants perceived visual elements in their physical environment. As such, I was able to describe how the participants detected information from external sources of information to structure and solve their design problems. Table 4.4 represents the frequencies and percentages of utterances indicating instances of each group of participants' access and use of external information sources.

**Table 4.4: Frequencies and percentages of utterances indicating external sources accessed and used**

		Frequency	Total number of utterances	Percentage
Group A	Workbooks	11	338	3.3
	Pictorial	85		25.1
	Sketches	135		40
	3D modelling	23		6.8
Group B	Workbooks	15	360	4.2
	Pictorial	112		31.1
	Sketches	165		45.8
	3D modelling	5		9.7
Group C	Workbooks	1	577	0.1
	Pictorial	312		54.1
	Sketches	95		16.5
	3D modelling	37		6.4

Table 4.4 indicates that each group of participants predominantly used their preliminary sketches and pictorial information to structure and solve their design problems. This finding contributed to my understanding of how novice designers are information detectors, and the subsequent role that technology teachers can play in planning rich learning environments with visual elements in which design cognition may be supported and enhanced in the technology learning environment.

In Figure 4.3 graphically represents the frequencies of utterances indicating the different external sources of information that were accessed during the TAPS process. Each group of participants used an extensive amount of external sources to structure and solve their design problems.



**Figure 4.3: Frequencies of external sources of information access and use**

The bar graph in Figure 4.3 visualises the different external sources of information that the learners accessed and used to structure and solve their design problems. Interestingly, none of the participants from the three groups found their workbooks as a useful source of information; instead, they used self-constructed sketches and pictorial information to structure and solve their design problems. A recent study has shown that both novice and expert designers prefer to use pictorial information as sources of inspiration during design processes (Gonçalves, Cardoso & Badke-Schaub

2014). Therefore, this study provided empirical evidence of how novices prefer to use pictorial information. However, findings from TE have also shown that novice designers are reluctant to use sketches to generate ideas, and would rather use 3D modelling (Welch, 1999; Hope, 2005). Therefore, this study also found contradictory evidence to what has been investigated regarding novice designers' sketching behaviour.

In Section 4.3.2, I have quantitatively analysed the internal and external sources of information each group of participants accessed and used. By analysing the instances and distribution of each group of participants' access and use of information sources, I was able to describe the extended design task environment (Haupt, 2013). As such, I described the availability of information sources in the technology learning environment. In the next section (4.3.3), I describe which sources of information each group of participants accessed and used during problem structuring and solving respectively.

### 4.3.3 Information access and use during the early phases of the design process

By counting the occurrences of the cognitive phases that each group of participants exhibited (4.3.1), as well as the information sources that they accessed and used (4.3.2), I was able to describe what sources of information each group of participants accessed and used during problem structuring and solving respectively. To this end, I was able to address my first sub-research question, namely,

*What sources of information do learners access and use during the early phases of the design process?*

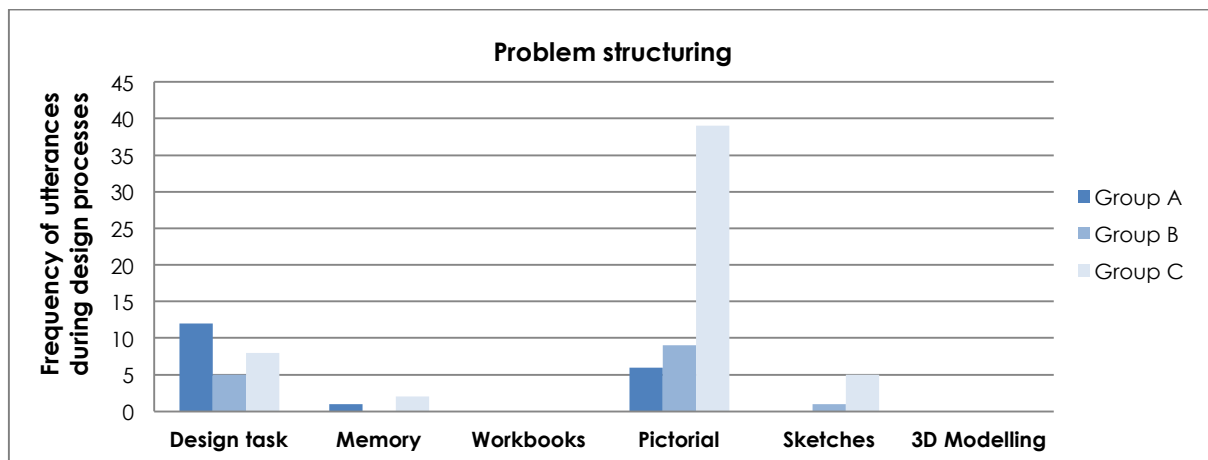
Table 4.5 summarises the frequencies of information access and use during each group of participants' cognitive phases.

**Table 4.5: Frequencies of information sources accessed and used by each group of participants during their cognitive phases**

Information source	Internal sources of information						External sources of information											
	Design Task			Memory			Workbook			Pictorial			Sketches			3D Models		
Groups	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
Problem structuring	12	5	8	1	0	2	0	0	0	6	9	39	0	1	5	0	0	0
Leaky phases	6	3	6	2	3	2	2	0	0	2	5	40	6	1	6	0	0	0
Problem solving	5	13	19	12	23	23	9	15	1	77	98	233	129	163	84	23	5	37

Table 4.5 indicates prominent trends discovered based on frequencies of information access and use of each group of participants during their cognitive phases. These trends are further explored in Figures 4.4 and 4.5.

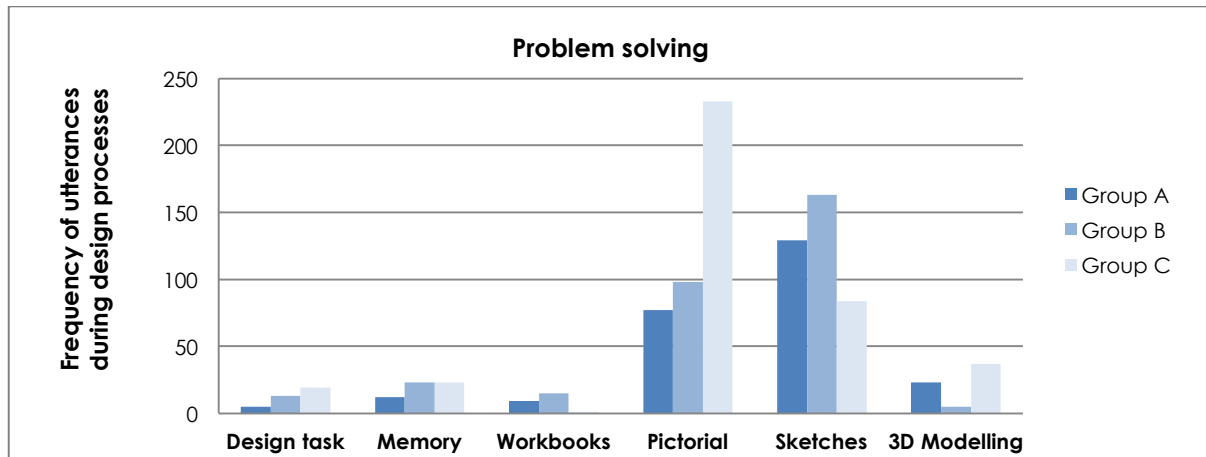
Each of their distinct cognitive phases is visualised using bar graphs in Figures 4.4 and 4.5 to show the most prominent patterns of information sources that each group of participants accessed and used during their cognitive phases. More specifically, Figure 4.4 represents the information sources that Groups A-C accessed and used during their problem structuring cognitive phases. Figure 4.5 represents the information sources that Groups A-C accessed and used during their problem solving cognitive phases. I found no significant trends in the Leaky phases.



**Figure 4.4: Frequencies of information access and use during problem structuring**

In Figure 4.5, the data patterns reveal that the participants in this study predominantly accessed and used the design task and pictorial information during their problem structuring phases. Therefore, the participants found internal information about the design problem and external pictorial information more useful than their workbooks, sketches and 3D modelling materials to structure their design problems. Figure 4.4 also indicates that the participants rarely accessed or used their workbooks or 3D modelling materials for problem structuring. This might have important implications for instructional planning in technology, since technology workbooks do not necessarily contain sufficient information to allow participants to structure their design problems.

Figure 4.5 represents the information sources that Groups A-C accessed and used during their problem solving cognitive phases.



**Figure 4.5 Frequencies of information access and use during problem solving**

Figure 4.5 indicates that all three groups predominantly accessed and used external pictorial information and their sketches as information sources during problem solving. Therefore, the participants for this study relied predominantly on external sources of information to solve their design problem. Furthermore, Figure 4.5 shows that the participants paid less attention to information sources including prior knowledge, their workbooks and 3D modelling materials. One implication for technology teachers might be to intervene in learners' design processes by explicitly reminding them of their prior knowledge.

In the previous sections (4.3.1 – 4.3.3), I was able to describe the quantitative patterns that I found when investigating the verbal protocols of each group of participants. In Section 4.3.1, I specifically focused on the cognitive phases that the participants exhibited during their design processes. In so doing, I was able to define their design problem solving spaces (Goel, 1995). In Section 4.3.2, I described the internal and external sources of information that the participants accessed and used during their design processes in order to describe their extended design task environments (Haupt, 2013). Consequently, in Section 4.3.3, I was able to describe what sources of information each group of participants accessed and used during problem structuring and solving respectively. In the next section (4.4.1), I qualitatively describe how each group of participants accessed and used sources of information in order to structure their design problems.

## 4.4 Qualitative data analysis

### 4.4.1 Information access and use during problem structuring

The purpose of this section is to describe how each group of participants structured their design problem by accessing and using sources of information. To this end, I was able to address my second sub-research question, namely,

*How do learners access and use internal and external information sources when structuring design problems?*

I was able to select a sample of instances showcasing the information access and usage of each group of participants. I describe these instances in the sequence in which they occurred during problem structuring by utilising temporal data. In order to qualitatively analyse these instances, I had to continuously interpret verbal utterances to reveal:

1. The mode of output, i.e. verbal or visual;
2. The content of the participants' thoughts;
3. The information sources that they accessed and used;
4. The operator applied to the information source;
5. The transformation related to problem structuring or solving.

In doing so, I was able to determine how the participants accessed and used information sources during their problem structuring phases. During my quantitative analysis, I already clustered utterances according to the early phases in the design process, as well as the sources of information that they accessed and used. For the qualitative analysis, I was able to interpret the clustered verbal utterances by interpreting how information sources were transformed by the application of mental operators. This revealed how the sources of information played a role in the transformation of the participants' understanding of the design problem and possible solutions during problem structuring. In Sections a-c, I focus on each group of participants individually to demonstrate how they accessed and used sources of information for problem structuring purposes.

#### **a) Group A – accessing and using information sources during problem structuring**

The following section describes the way in which Group A's participants accessed and used sources of information during problem structuring. Prior to the particular instance of problem structuring demonstrated in Excerpt 4.1, each of Group A's participants received their design tasks for the first time (see Appendix A). After receiving their design tasks, the participants read and responded to internal information posed in the design task. In Excerpt 4.1, the participants paid attention to the second instruction, namely, *"How will the machine make work quicker and faster?"* In this way, participants could transform internal and external information sources to propose a new design requirement.

### Excerpt 4.1

**P11 02:00**

*How will the machine make work quicker and faster? It will pick up*

**P12 02:06**

*It will move around easier*

**P11 02:09**

*Ja, it will move around easier and*

**P12 02:16**

*Make the workers, make the jobs faster*

**P11 02:20**

*Like it will move around and pick up like more than one, instead of one, it maybe picks up two or three.*

During Group A's dialogue, demonstrated in Excerpt 4.1, P11 and P12 responded to internal information about the design problem, which dealt with content about the design objectives, when they considered how a machine can make work quicker and faster. They asserted that a machine that moves around while picking up logs should make the work easier than current manual logging practices. As such, they were considering the people in the logging environment. Furthermore, P11 also suggested that a machine picking up more than one log at a time could make the work faster, thereby addressing another design objective. In Photograph 4.4, evidence of how P11 accessed and transformed an external information source is provided.



*P11 perceives the shape of a highlighter and associates it with a log to be picked up by a machine.*



*When P11 picks up the highlighter, he is able to reason why using a machine can make work quicker and faster*

**Photograph 4.4: Perceiving affordances in the technology learning environment**

**Photograph 4.5: Acting on affordances in the technology learning environment**

In Photograph 4.4, P11 perceived the shape of a highlighter, associating it with a log to be picked up. In this way, the participants perceived a visual element in their physical surrounding. By acting on the perceived 'shape' and picking up the highlighter, P11 was able to transform the perceived information by applying an elaborating operator to indicate how a machine can make the work go faster for the workers. When P11 picked up the highlighter, P12 also applied an elaborating operator in stating that a machine will make the workers' jobs faster, thus, enabling Group A to gain a better understanding of the design objective. Furthermore, while lifting the highlighter, P11 also evaluated the 'size' of the logs, and proposed that more than one log can be lifted at a time to make the work go faster, thereby creating a new design requirement. As such, it seems as if the participants were

able to transform their initial understanding of their design problem by (1) reading internal information about the design problem; (2) perceiving external information embodied in the shape of the highlighter; (3) evaluating the action and size of the highlighter; and (4) proposing a new design requirement.

Therefore, it appears as if the sequence in which the participants accessed and used sources of information, which contained content about the people involved, the logging environment and the design objectives, contributed to their problem structuring when they were able to formulate a design requirement for their design solution. This design requirement enhanced the participants' problem structuring by helping them to understand their design problem – to make the work go faster in current manual log-loading practices.

Another instance where Group A engaged in problem structuring occurred when the participants were again reading and responding to internal information about the design problem. Prior to this instance, the participants were systematically following instructions from their design task. The instructions in the design task required them to '*consider the environment in which the machine must function*'. In particular, the participants were deliberating "*how high will the machine have to lift the logs*". Excerpt 4.2 demonstrates how the participants considered the height to which the logs must be lifted. This statement contained content about the behaviour of the machine, which led the participants to content about the context.

#### Excerpt 4.2

**P13 06:26**

*How high will it be able to go?*

**P11 06:27**

*How high?*

**P13 06:29**

*Cause it seems like the truck is kind of high*

**P11 06:52**

*How high? It will actually depend on the truck, how big it is and how wide it is.*

During the problem structuring instance, P13 read internal information contained in the design task. The internal information required Group A to find missing information about the behaviour of a machine in the logging environment context by deliberating about the height to which the logs should be lifted. Therefore, reading information about the design problem initiated a problem structuring phase. P13 subsequently perceived visual elements of 'size' in the picture of the transport truck to which the logs had to be lifted, as demonstrated in Figure 4.6.



**Figure 4.6: External pictorial information about the design problem context (Jose, 2011a)**

By paying attention to the problem context, specifically the size of the transport trucks in Figure 4.6, P13 was able to indicate a measure of the height to which the logs must be lifted. Consequently, P11 evaluated that the height to which the logs must be lifted would be relative to the size of the transport trucks. However, limited transformation of the participants' understanding of the problem context took place, as they were not immediately able to specify a height to which the logs should be lifted. As a result, the participants delayed their problem structuring. This postponement is reflected in Excerpt 4.3, when the participants required the information during a problem solving cognitive phase. During this cognitive phase, the participants were sketching the structure of their design solution when P13 suddenly remembered to consider the height to which the logs should be lifted.

#### **Excerpt 4.3**

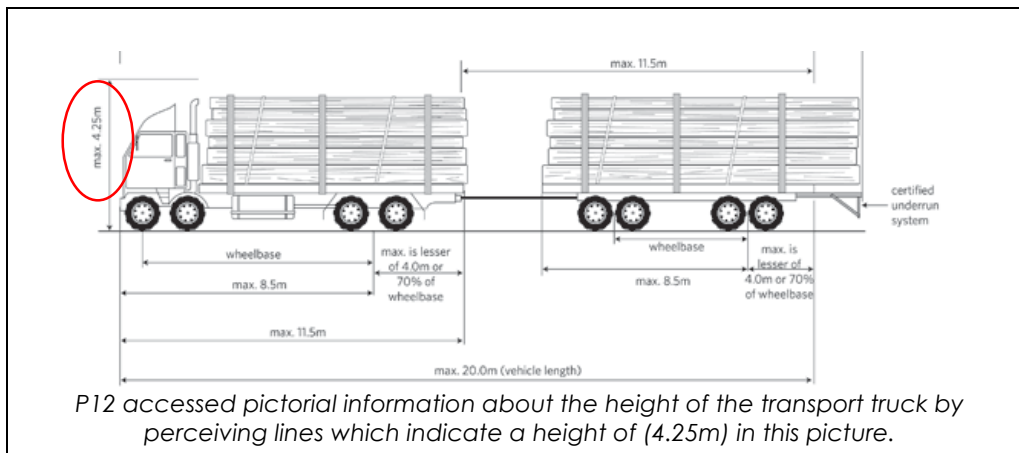
**P13 29:43**

*Oh! We should also probably check how high that we can get a truck to lift the logs!*

**P12 29:49**

*4.25 (height of truck)*

In Excerpt 4.3, P13 asks Group A to consider the height of the transport truck to which the logs should be lifted. P12 responds to her request by perceiving 'lines', shown in Figure, 4.7, which revealed the height of the transport truck.



**Figure 4.7: Pictorial information about the dimensions of transport truck (NZ Transport Agency, 2011)**

As P12 accessed embodied information about the dimensions of a logging truck in Figure 4.7, Group A's participants were able to use the embodied information to formulate a design specification for their design solution. This design specification entailed that the logs should be lifted at least 4.25m, which is consistent with the truck's height. As such, the participants were able to transform their initial understanding of the problem context, first instantiated in 06:26 (Excerpt 4.2), by (1) reading internal information about the design problem context; (2) perceiving embodied information in a picture about the size of a transport truck; (3) postponing problem structuring from 06:26 to 29:43; (4) perceiving embodied pictorial information in a 'line' indicating the height of the transport truck; and (5) proposing a design specification of 4.25m to which the logs should be lifted. Therefore, it appears as if the sequence in which the participants accessed and used sources of information contributed to their problem structuring when they were able to propose a design specification for their design solution. This design specification enhanced the participants' problem structuring by helping them to understand the context of their design problem – to consider the height to which the logs should be lifted. The problem structuring was also evident in the contextual information, which the participants needed during a problem solving phase while thinking about the structure of their design idea.

**b) Group B – accessing and using information sources during problem structuring**

The following section describes the way in which Group B's participants accessed and used sources of information during problem structuring. Prior to the particular instance of problem structuring demonstrated in Excerpt 4.4, each of Group B's participants received their design tasks for the first time. After receiving their design tasks, the participants read and questioned the internal information posed in the design task instructions. In Excerpt 4.4, the participants paid attention to the first instruction, namely, 'How will the environment in which the machine operates affect its operation?' At first, this instruction seemed unclear; however, I intervened by showing the participants pictorial information in which they could find missing information.

#### Excerpt 4.4

**P3 02:59**

*How will the environment in which the machine operates affect its operation?*

**P3 03:16**

*I do not understand this question.*

**P4 03:20**

*Let's go to the other one then.*

**R 03:21**

*Ok, I can quickly explain that. How will the environment – if you look at these pictures the environment in which this machine will be able to pick up logs. Ok, how will this environment influence the way this machine will work?*

**P3 03:31**

*Yes.*

**R 03:49**

*How do you think this will influence how the machine will work?*

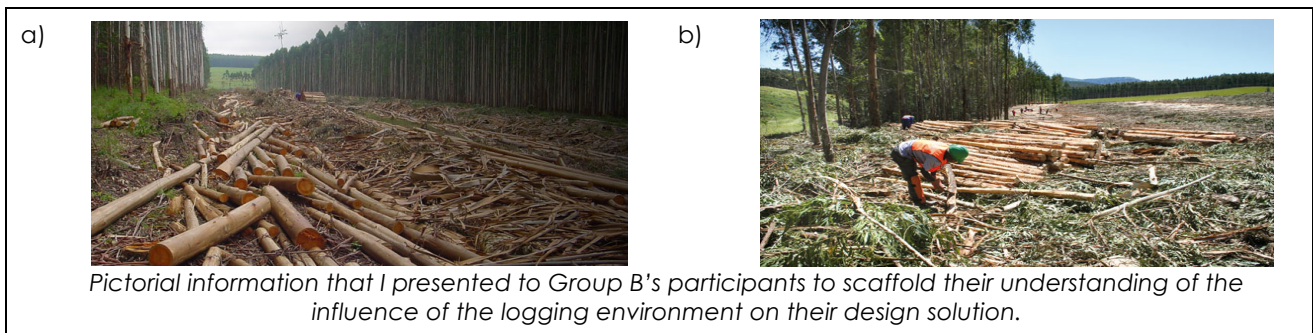
**P4 03:53**

*The machine won't work properly because there are many logs on the floor so,*

**P3 04:03**

*So sir if we make the one, which has wheels and can travel, will it be able to move around? Maybe because I see there is a way here.*

During their dialogue, presented in Excerpt 4.4, the participants were unsure of what the internal information in the design task meant as they considered how the environment would influence their design solution. This uncertainty was evident when P3 said '*I do not understand this question*'. My role as the researcher hence changed from observer to participant when I intervened to scaffold the participants' thinking process by introducing external pictorial information about the context, illustrated in Figure 4.8.



**Figure 4.8: Pictorial information a) (Revolution, 2015) and b) (SA Forestry Magazine, 2011a) of the logging environment**

When I introduced the pictorial information (Figure 4.8) to the participants, they were able to perceive the 'surface' area of logging environments. Subsequently, P4 identified the lack of space in the logging environment and proposed this as a design constraint during 03:53, which I could interpret as a problem structuring activity. P3 responded to the identified design constraint by applying a proposed operator, that their design solution might require wheels, as she perceived embodied information about a smooth 'texture' as a path on which a machine could travel in the logging environment (see Figure 4.9).



**Figure 4.9: Information accessed in a picture about a road in the logging environment (SA Forestry Magazine, 2011a)**

In Figure 4.9, P3 identified a road in the logging environment on which a machine could travel, which contributed to the participants' understanding of the logging environment. Identifying the road in the logging environment hence addressed the design constraint proposed during 03:53. In this way, the participants were able to transform their understanding of the logging environment in which the machine must function by (1) reading internal content about the context from the design task; (2) perceiving embodied information about the 'surface' of the logging environment, resulting in the proposal of an environmental constraint; and (3) perceiving the smooth texture of the road in the logging environment to address the design constraint. Perceiving embodied information about the logging environment in this way transformed the participants' initial uncertainty about the effects of the logging environment on their design solution. This transformation was evident when P4 formulated a design constraint based on the perceived information from Figure 4.8, as well as in P3's recognition of a road in the logging environment in Figure 4.9. Therefore, it seems as if Group B's access and use of information contributed to their problem structuring by guiding them to understand the logging environment in which their design solution should function. In addition to this, Figure 4.9 also facilitated a Leaky phase when P3 immediately proposed structural content for their design idea by suggesting that their idea should have wheels that can move around in the logging environment.

Another instance where Group B engaged in problem structuring occurred shortly after the previous instance demonstrated in Excerpt 4.4. While the participants were discussing how the environment would influence the machines' operation, they were also instructed in the design task to consider 'how high the machine will have to lift the logs'. Participants therefore seemed to find missing information about the design context.

#### Excerpt 4.5

**P3 04:57**

How high will it lift the logs? Let me check out the how tall the truck is

**P4 05:28**

Page?

**P3 05:30**

Page 4. Because the truck is 4.25 meters max. So if the truck can lift the logs about 3.25 will it be fine? Or more than that?

**P4 05:59**

I think more

**P3 06:31**

I think that the machine must lift the same height as the truck, don't you think so?

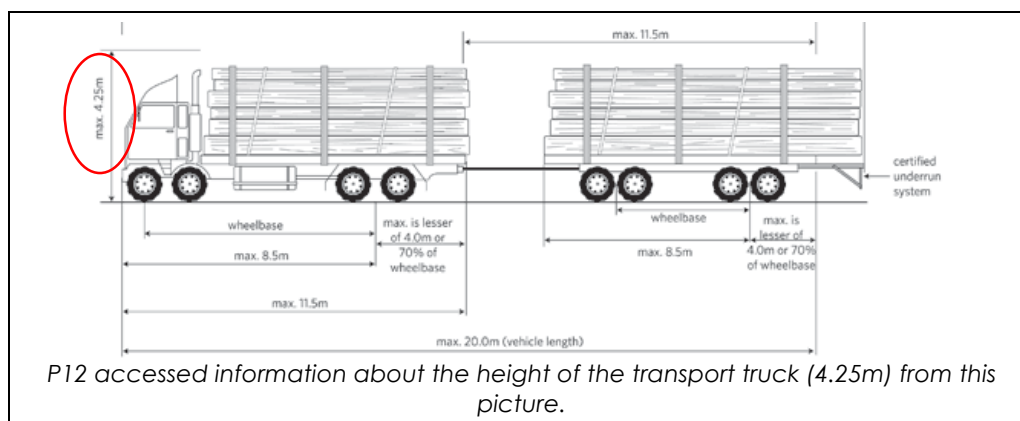
**P4 06:36**

Yes.

**P3 06:37**

4.25.

Excerpt 4.5 demonstrates the sequence in which the participants considered the height to which the logs must be lifted. As P3 read the internal information from the instructions in the design task aloud, she referred back to pictorial information about the dimensions of a logging truck. Figure 4.10 shows the pictorial information that Group B accessed and used to determine the height to which the logs should be lifted.



**Figure 4.10: Pictorial information about the dimensions of the transport truck (NZ Transport Agency, 2011)**

By identifying and perceiving a 'line', which embodied information about the height of the transport truck in pictorial information, which is illustrated in Figure 4.10, P3 was able to propose that their design solution should lift the logs approximately 3.25m. However, further elaboration from P4 led Group B to decide on a design specification of 4.25m, which was consistent with the truck's height in Figure 4.11. In this way, the participants were able to transform their uncertainty about the height to which the logs should be lifted by (1) reading internal information about the design problem in the design task instructions; (2) perceiving embodied information about the height of the truck to determine the height of the transport truck; and (3) proposing a design specification of 4.25m to which the logs should be lifted. It seems as if the participants found missing information about the design context when their understanding of the height to which the logs should be lifted was transformed by their perception of embodied information. This transformation occurred when the participants proposed a design specification based on embodied information shown in a 'line' to indicate the dimensions of a transport truck. In so doing, Group B was able to structure the design problem context by specifying the height to which a machine should lift logs.

Similar problem structuring behaviour was also observed from Group A's participants in Section a). One similar pattern that emerged from the qualitative analysis is the central role that internal information in the design task plays as input information in the participants' design processes. It seems as if the input information, i.e. the height to which the logs should be lifted, required the participants of Group A and B to seek information about the problem context. The picture represented in Figure 4.10 provided the participants with useful embodied information about the dimensions of a transport truck, which subsequently transformed the input information into a design specification.

### **c) Group C – accessing and using information sources during problem structuring**

The following section describes the way in which Group C accessed and used sources of information to structure their design problem. Prior to their problem structuring demonstrated in Excerpt 4.6, each of Group C's participants received their design tasks for the first time. After receiving their design tasks, the participants read and responded to internal information posed in the design task instructions. In Excerpt 4.6, the participants paid attention to the first instruction, namely, '*How will the environment in which the machine operates affect its operation?*' Subsequently, the participants identified embodied information about the surface layout of the logging environment, which created a perceived slant.

#### Excerpt 4.6

**P6 01:34**

*How will the environment in which the machine will operate affect its operation?*

**P7 01:54**

*So that means, if maybe the logs are up*

**P6 02:24**

*How will they pick the*

**P7 02:27**

*Ja, mos, if the logs are on a (hill), what can I say for this one?*

**P6 02:48**

*We will come back to this one.*

A problem structuring cognitive phase was instantiated when the participants of Group C read guidelines from their design task during 01:34, asking them to consider 'How will the environment in which the machine will operate affect its operation?' At first, the participants were unsure what this prompt meant. P7 subsequently accessed pictorial information about the logging environment, illustrated in Figure 4.11.



**Figure 4.11: Pictorial information about a hill in the logging environment (Jose, 2011c)**

In Figure 4.11, P7 perceived embodied information regarding a hill by recognising a 'slant' in the logging environment that might affect how their design solution would operate in the logging environment. However, Group C's participants did not immediately use this information to structure their design problem. Instead the participants decided to postpone their problem structuring phase when P6 stated that "We will come back to this one". As such, their problem structuring occurred during two later problem solving phases when they considered the structural content of existing solutions for their design problem. Excerpt 4.7 reveals the first instance of problem structuring when Group C transitioned from a problem solving phase to considering a hill in the logging environment as a design constraint.

#### Excerpt 4.7

**P7 04:03**

*If it's something like this gear and crank system, that means that the logs and the truck will have to be probably at the same place, cause this thing doesn't have wheels to move*

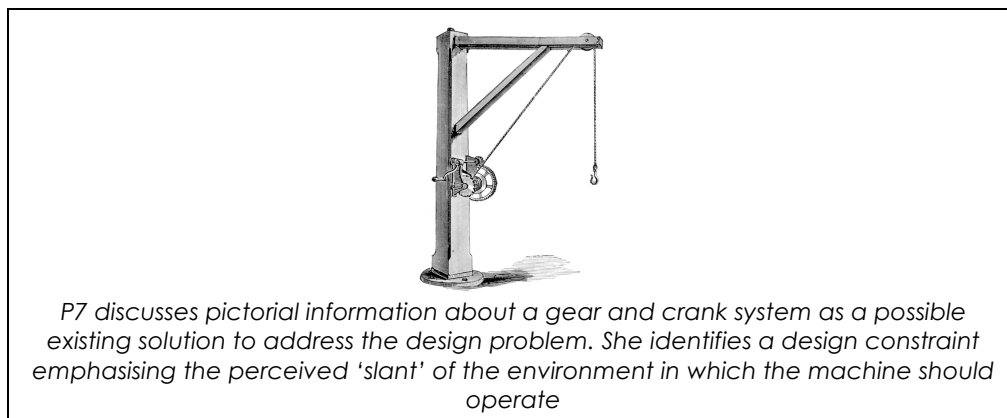
**P6 04:13**

*Ya, that's what I'm saying*

**P7 04:15**

*What if they move like on these examples, as you can see this place looks like it's going up like a hill or something. Then a truck won't be able to move up, something like a hill, something like this.*

Prior to the dialogue demonstrated in Excerpt 4.7, the participants discussed the existing structure and behaviour of possible solutions to their design problem. One of the possible existing solutions was a gear and crank system, shown in Figure 4.12.



**Figure 4.12: Pictorial information of a gear and crank system (Edwin Harrington, Son & Co., 2010)**

Discussing the gear and crank system shown in Figure 4.12 led P7 to propose a design constraint, which caused Group C's problem solving to transition into a Leaky phase. The design constraint that Group C identified emphasised the slant in the logging environment in which the gear and crank system should operate. They were able to derive this design constraint by discussing the nature of the gear and crank system, reflected in Figure 4.12, and recalling information previously discussed in Excerpt 4.6. In this way, Group C's participants were able to structure their design problem by (1) perceiving pictorial information about the gear and crank system as an existing solution; (2) recalling information about a hill in the logging environment; and (3) proposing a design constraint based on the topography of the logging environment in which the gear and crank system should operate. It seems as if the participants found missing information that they needed during problem solving when they recalled perceived embodied information about the slant in the logging environment. This transformation occurred when the participants were able to propose a design constraint in discussing the structure of a gear and crank system. As such, Group B was able to structure their problem by understanding the logging environment in which their design solution would be operated by formulating a design constraint.

During the second instance of problem structuring, shown in Excerpt 4.8, Group C considered the environment in which their machine would operate again.

#### Excerpt 4.8

**P7 22:12**

*But you think the logs and the trucks will be at the same place? Because there are some places where people cut the trees, and a truck can definitely not go in*

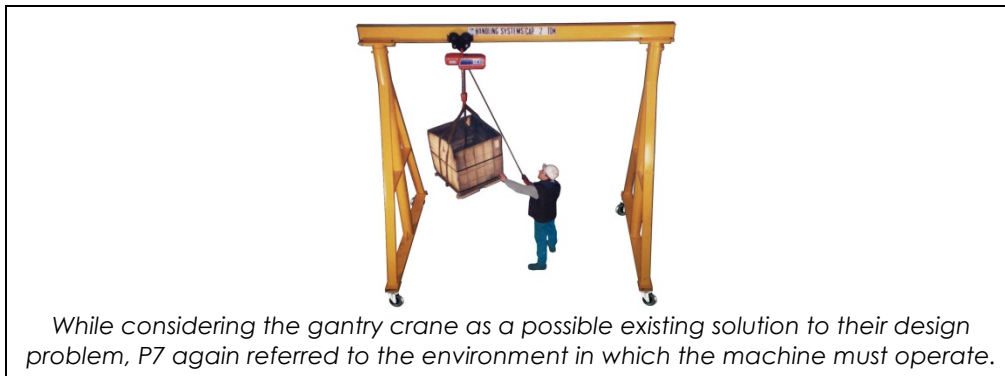
**P6 22:26**

*They can make a plan and maybe move the logs ne and the tree. As you can see here. There's a place. It doesn't mean if they cut off trees, ne, all over the place there will be trees falling off there will be a certain place*

**P7 22:46**

*Yeah I understand, but there are some places where, not even a small cart can get in*

Before this particular instance shown in Excerpt 4.7, the participants were discussing a gantry crane as a possible existing solution to their design problem. The gantry crane that the participants discussed is shown in Figure 4.13.



**Figure 4.13: Pictorial information of a gantry crane (Allbiz, 2010)**

Discussing the gantry crane, shown in Figure 4.13, led P7 to identify another design constraint in the logging environment, which caused Group C's problem solving to transition into a Leaky phase. The design constraint that Group C proposed emphasised embodied information about the 'position' of the logs from an accessible place to load the logs. Subsequently, in the pictorial information identified in Figure 4.14, P6 noticed a path that was suggested by the smooth 'texture' where the logs can be loaded onto the transport truck. Interestingly, Group B also identified this road, previously discussed in Figure 4.9.



**Figure 4.14: Pictorial information accessed about the accessibility of the logs (SA Forestry Magazine, 2011a)**

Figure 4.14 depicts the pictorial information that P6 used to address a design constraint. The design constraint, namely the truck's access to the logs, could be addressed when P6 identified a place in the logging environment where a machine can lift logs onto a truck. As such, Group C's participants were able to structure their design problem by (1) perceiving embodied information about the shape of the gantry crane as an existing solution; and (2) proposing a design constraint based on the truck's position from the logs; and (3) perceiving a place in the logging environment where a machine can lift logs onto a truck. It seems as if the participants' uncertainty about the influence of the logging environment on the design solution was transformed by their access and use of embodied pictorial information. This transformation occurred when the participants were able to address a design constraint by referring to pictorial information. In this way, Group B was able to structure their problem by transforming their understanding of the logging environment by perceiving embodied information.

In the next section (4.4.2), I qualitatively describe how each group of participants accessed and used sources of information in order to solve their design problems.

#### 4.4.2 Information access and use during problem solving

The purpose of this section is to describe how each group of participants solved their design problems by accessing and using sources of information. To this end, I was able to address my third sub-research question, namely,

*How do learners access and use internal and external sources of information to generate new information when solving design problems?*

I was able to select a sample of instances showcasing the information access and usage of each group of participants. I describe these instances in the sequence in which they occurred during problem solving. In Sections a-c, I focus on each group of participants respectively to demonstrate how they accessed and used sources of information for problem solving purposes.

**a) Group A – accessing and using information sources during problem solving**

The following section describes how Group A accessed and used sources of information during problem solving. Prior to the particular instance of problem solving, shown in Excerpt 4.9, the participants considered the first instruction in the design task regarding the environment in which the machine should operate. However, they only engaged with the instruction for two and a half minutes, after which they paid attention to the second instruction, which was: *Think about the movement the machine will need to perform. Which mechanisms can you use to pick up and hold the logs? Lift the logs? Create different movement in different parts of the machine?* These instructions seemed to focus on the behaviour of artefacts, and led the participants to find information about existing solutions.

**Excerpt 4.9**

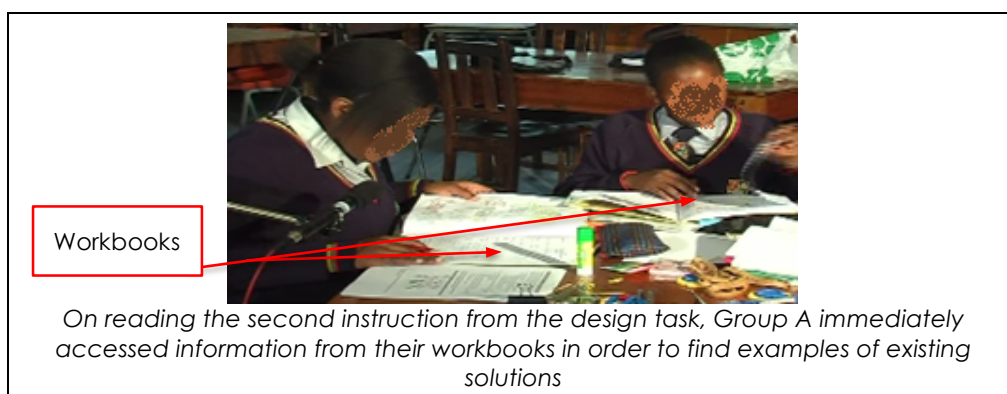
**P11 02:33**

*Think about the movement the machine will need to perform. Which mechanisms can you use to pick up and hold the logs? And lift the logs? Create different movement in different parts of the machine?*

**P11 02:58**

*Why? For the hydraulic system, it uses oil to control machines. Reduce friction...I think we should use the hydraulic system cause it says that it uses oil to control machines, reduce friction, does not freeze easy as water for example let's say it's raining, then it won't freeze.*

Immediately after reading the instruction from the design task during 02:33, Group A accessed their workbooks which contained the work they had done on mechanical systems and control during their second term. It seemed as if they were looking at the information in their workbooks to investigate appropriate existing solutions to their design problem after reading internal information from the design task. Photograph 4.6 shows how Group A's participants accessed their workbooks to find information about existing solutions.



**Photograph 4.6: Group A accessing information in their workbooks**

By looking at information in the workbooks, as illustrated in Figure 4.6, P11 was able to propose a hydraulic system as one existing solution that might address the design problem. P11 also justified its use by reading information from her workbook. The justification entailed that the oil in a hydraulic system will not freeze in cold environmental conditions. However, Group A did not commit to using the hydraulic system and P12 subsequently accessed pictorial information about a pulley system, demonstrated in Excerpt 4.10.

#### Excerpt 4.10

**P12 03:42**

*I was also thinking of this idea.*

**P13 03:46**

*Page?*

**P12 03:48**

*5.*

**P11 03:51**

*Pulley system*

**P11 03:54**

*But then if we use the pulley system, like the people who get tired of pulling*

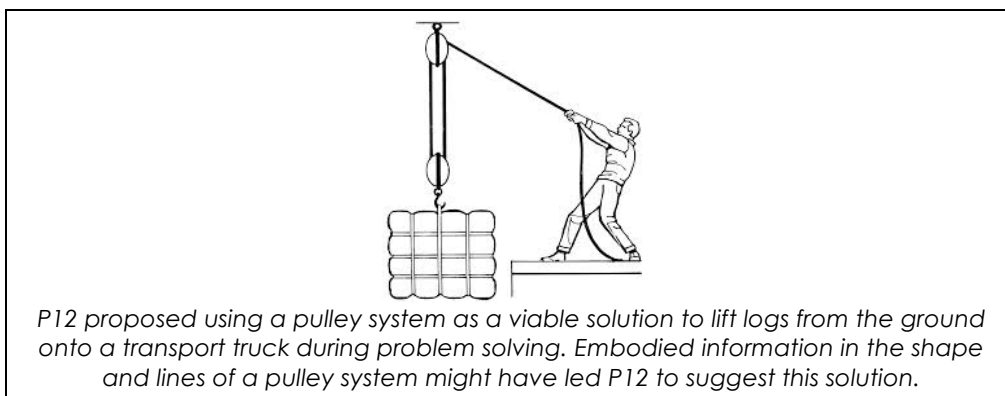
**P13 03:58**

*Pulling and what if they have more weight?*

**P11 04:01**

*So then it will have to find something that will pull at if we use the pulley system*

In Excerpt 4.10, P12 proposed that a pulley system might be a viable solution, which she had perceived in the pictorial information. It seems as if the shape and lines used to depict a pulley system in Figure 4.15 triggered P12's proposal of a pulley system.



**Figure 4.15: Pictorial information of a pulley system (The Mighty Quill, 2014)**

As P12 proposed a pulley system, shown in Figure 4.15, P11 and P13 evaluated the pulley system on the basis of a recalled design requirement to make work easier for the manual workers. It seemed as if P13 evaluated the pulley system on the basis of embodied information in the posture of the worker pulling a heavy load. By evaluating the behaviour of a pulley system while a worker is operating it, P11 and P13 were able to formulate a design limitation of using a pulley system. This limitation

entailed that the pulley system would make workers' jobs harder if they had to lift heavy loads. By proposing a possible design limitation, it seemed as if the participants did not commit themselves to the pulley system, and proceeded to find alternative solutions from pictorial information. In Excerpt 4.11, P13 proposed a gear and crank system that she had perceived in the pictorial information.

#### Excerpt 4.11

**P13 04:07**

*And then the gear? Wouldn't it work? I'm not sure but will it work?*

**P12 04:14**

*This one?*

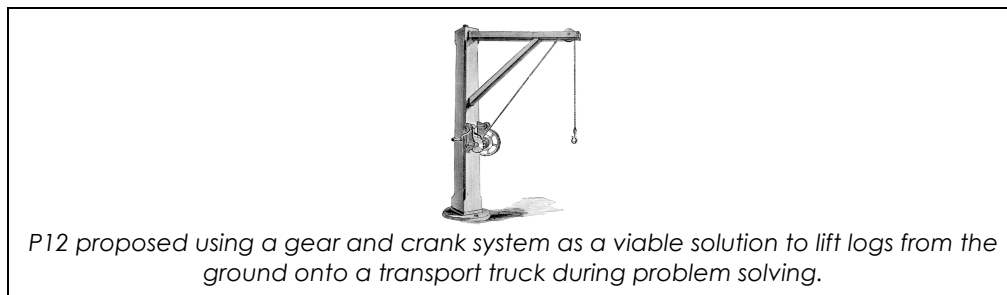
**P13 04:15**

*Yes, yes*

**P11 04:19**

*The gear and the crank system. But then when we, like we want something that like when we using it, it doesn't pick up one, or at least it should pick up two or more.*

In Excerpt 4.11, P13 proposed the use of a gear and crank system, which she had perceived in the pictorial information. Figure 4.16 illustrates the picture of a gear and crank system that P13 accessed.



**Figure 4.16: Pictorial information of a gear and crank system (Edwin Harrington, Son & Co., 2010)**

As P13 proposed a gear and crank system, shown in Figure 4.16, P11 evaluated the gear and crank system by recalling a design requirement of lifting more than one log at a time. It seems as if P11 recognised a limitation in the behaviour of the gear and crank system. P11 was able to recall the design requirement that they formulated during 02:20, discussed in 4.4.1.a), to evaluate how a possible design solution should behave to fulfil its function. Based on the design requirement to lift more than one log at a time, Group A further sought more alternative solutions. Subsequently, they perceived pictorial information about hydraulic tongs as a possible existing solution. Excerpt 4.11 indicates how P11 evaluated the hydraulic tongs as a viable solution, based on their design requirement to pick up more than one log at a time.

**Excerpt 4.12**

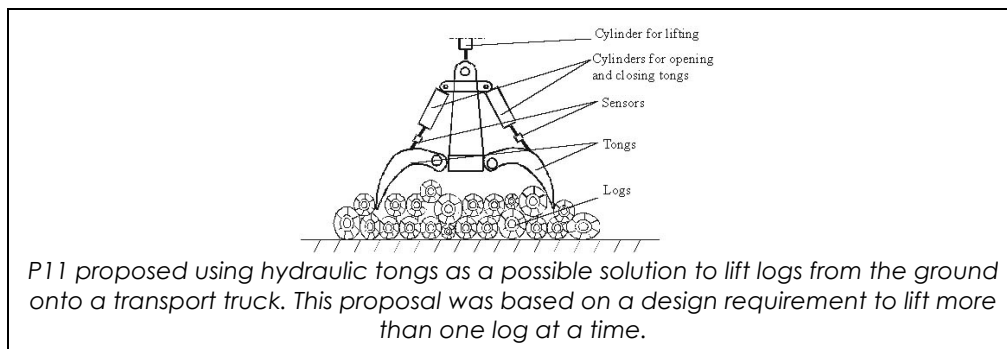
**P11 04:43**

*It should be something like the hydraulic thing or the hydraulic tongs. That will pick up more instead of one. Cause if it does one, it will be slow*

**P13 04:56**

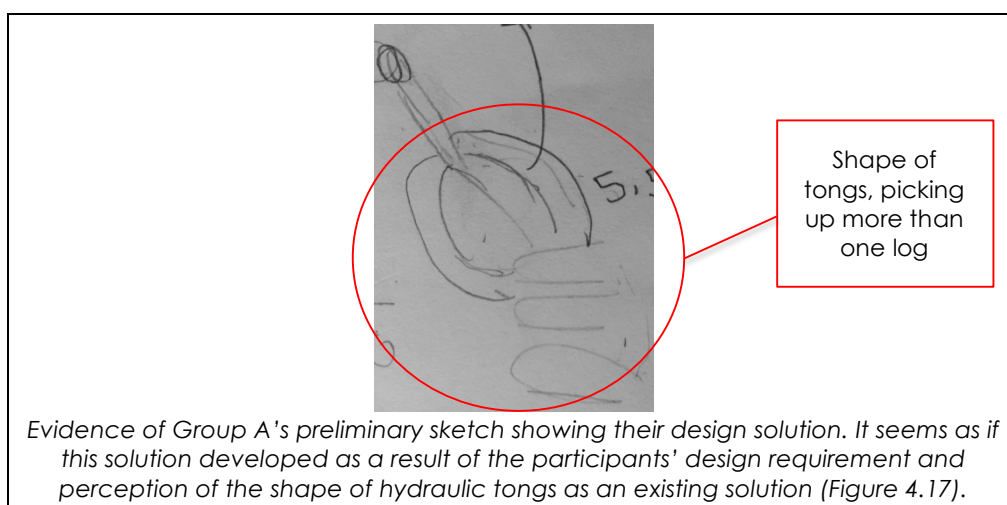
*And not finish in time*

Excerpt 4.12 shows how P11 perceived the shape of the hydraulic tongs as a possible solution on the basis of their requirement to pick up more than one log at a time. Figure 4.17 illustrates the picture that P11 perceived.



**Figure 4.17: Pictorial information of hydraulic tongs (Wang, LeDoux & Wang, 2005)**

As P11 accessed pictorial information of hydraulic tongs in Figure 4.17, Group A's participants were able to use their previously formulated internal design requirement to evaluate the usability of the hydraulic tongs. By evaluating the pictorial information of the hydraulic tongs, P11 was able to qualify the behaviour of hydraulic tongs in picking up multiple logs as a suitable design solution. This qualification was based on the participants' requirement to lift more than one log at a time in order to make manual loggers' work go faster. However, it was not until later in the design process that the decision to use a tong structure was externally represented. Photograph 4.7 showcases how the participants externally represented a preliminary solution that realised their design requirement.



**Photograph 4.7: Preliminary sketch made by Group A (31:54)**

Photograph 4.6 illustrates the external representation that the participants made of a structure that seems to represent the shape of tongs that can lift more than one log at a time. It seems as if this design solution developed as a result of the systematic access to and use of various sources of information during their problem solving phases. The incremental transformation of information sources was evident in the way the participants: (1) read internal information from the design task; (2) perceived information about hydraulic systems from their workbooks; (3) evaluated pictorial information about a pulley system; (4) proposed a limitation of using a pulley system based on a recalled design requirement to make the work easy; (5) perceived and evaluated pictorial information about a gear and crank system; (6) proposed a limitation of a gear and crank system based on a recalled design requirement to make the work faster; (7) perceived and evaluated pictorial information about hydraulic tongs; (8) qualified hydraulic tongs for picking up multiple logs on the basis of a recalled design requirement, and (9) externalised the design requirement in a preliminary sketch. Therefore, it appears as if the sequence in which the participants transformed information sources, focusing on finding a suitable solution, contributed to their problem solving phase.

Another problem solving phase of Group A includes an instance when the participants used pictorial information to develop a design solution in which a pulley system was used. Before this particular instance, presented in Excerpt 4.13, the participants were instructed to consider “Which mechanisms can you use to pick up and hold the logs? Lift the logs? Create different movement in different parts of the machine?” and subsequently proposed using a pulley system as a possible solution. However, as demonstrated in the discussion in Excerpt 4.9, the participants identified a design limitation which entailed that the pulley system would make workers' jobs harder if a worker had to lift heavy loads. In Excerpt 4.13, P13 proposed a plan to address the design limitation.

#### Excerpt 4.13

**P13 05:32**

*But I think for the pulley system we can maybe use two or three people that can actually pull it, so that they don't get tired, so that they can switch also and those three that are tired. Don't you think so?*

**P11 05:43**

*Ja.*

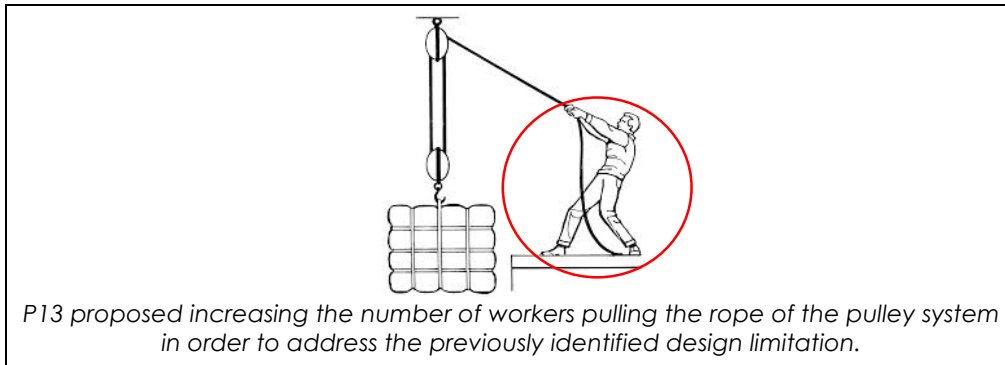
**P12 05:45**

*And the other thing, there's many workers*

**P11 06:09**

*So we going to use the pulley system and then the people will pull the rope*

Excerpt 4.13 displays the dialogue between Group A's participants to address a design limitation that they formulated when perceiving and evaluating pictorial information about a pulley system. The picture that the participants evaluated is displayed in Figure 4.18.



**Figure 4.18: Pictorial information of a pulley system (The Mighty Quill, 2014)**

By evaluating the picture displayed in Figure 4.18, P13 was able to address the design limitation by proposing that two or three workers could make the work easier instead of using one person only. Subsequently, P12 justified P13's proposal by perceiving and elaborating on a picture showing that there are many workers in the logging environment. This picture is shown in Figure 4.19.



**Figure 4.19: Pictorial information of the workers in a logging environment (SA Forestry Magazine, 2011b)**

By perceiving and elaborating on the number of workers in the logging environment, shown in Figure 4.19, P12 was able to justify P13's proposal to include more than one worker pulling the rope on a pulley system to lift the logs. Furthermore, perceiving and elaborating on a picture of the workers in the logging environment caused the participants to engage in a Leaky phase. The Leaky phase was facilitated by the participants' need for information about the problem context. In this way, the participants transformed the design limitation of a pulley system into a design requirement by (1) reading internal information from the design task; (2) evaluating pictorial information about a pulley system; (3) proposing a limitation of using a pulley system based on a recalled design requirement to make the work easy; (4) perceiving and evaluating the number of workers in the logging environment; and (5) proposing a design requirement entailing more than one worker to operate the pulley system.

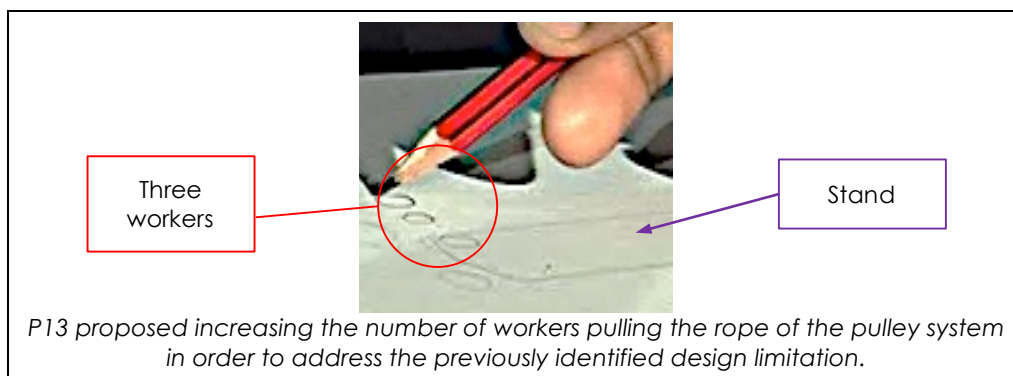
The proposed design requirement to include more than one worker to operate the pulley system was also evident when P13 started to draw the preliminary sketch of the pulley system. While sketching the design solution, P13 discussed and elaborated on the position of three workers. P13's description of the preliminary sketch is shown in Excerpt 4.14 and the concurrent sketch in Photograph 4.8.

#### Excerpt 4.14

**P13 09:07**

*And then we should make possible a stand where a person, those three people or that, maybe it can be one person there, and another person there and another person there because he will be on the top of the system so that he can pull and the rest will pull it downwards*

Excerpt 4.14 reveals how P13 conceptualised a design solution based on the proposed design requirement to include three workers. In her description of the sketch, she elaborated on the effect of three workers on the structure of the pulley system. Photograph 4.8 shows how P13 transformed the internal design requirement by conceptualising the structure of a design solution and externalising it in a preliminary design sketch.



**Photograph 4.8: Preliminary design sketch generated by Group A (09:07)**

Photograph 4.8 shows P13's conceptual structure of a design solution in her preliminary sketch. This sketch was seemingly based on the internal design requirement to include more than one worker to operate a pulley system. It seems as if Group A was able to transform the internal design requirement of using three workers to operate a pulley system by (1) proposing the design requirement; (2) elaborating and sketching three workers on the structure of the design solution, thereby (3) addressing the previously perceived limitation. Therefore, it appears as if the sequence in which the participants accessed and used information sources contributed to their problem solving when they were able to transform an internal requirement into a preliminary sketch. This preliminary sketch enhanced the participants' problem solving by helping them to understand how their pulley system would be operated.

In the next section (b), I discuss how Group B was able to use internal and external sources of information, which contributed to their design problem solving cognitive phase.

**b) Group B – accessing and using information sources during problem solving**

In the following section, I describe instances of Group B's access and use of information sources during problem solving. Prior to the specific instance of problem solving, shown in Excerpt 4.15, Group B's participants received their design task and instructions. I read the design task aloud and explained the instructions to the participants. P3 immediately engaged in problem solving despite the instructions that were given in the design task.

**Excerpt 4.15**

**R 02:30**

*What are you busy drawing?*

**P3 02:36**

*Sir, I am drawing the place where the person can sit, then I am going to start drawing the hydraulic crane*

**R 02:45**

*Ok*

**P4 02:47**

*But then, we have to start with the questions first, before we do the sketches.*

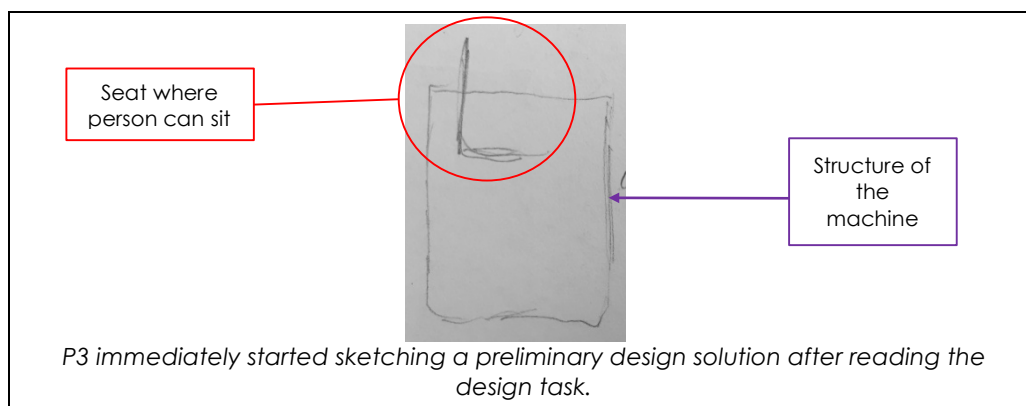
**P3 02:52**

*Which questions?*

**P4 02:53**

*The instructions, page 2.*

Excerpt 4.15 shows how Group B immediately started with problem solving after I had read and explained the design task to them. P3 started to sketch a design solution based on her memory and perceived pictorial information about a hydraulic crane. Photograph 4.9 shows the preliminary sketch that P3 started to draw of a preliminary design solution. However, P4 interrupted the problem solving phase by suggesting that they should look at the instructions first.

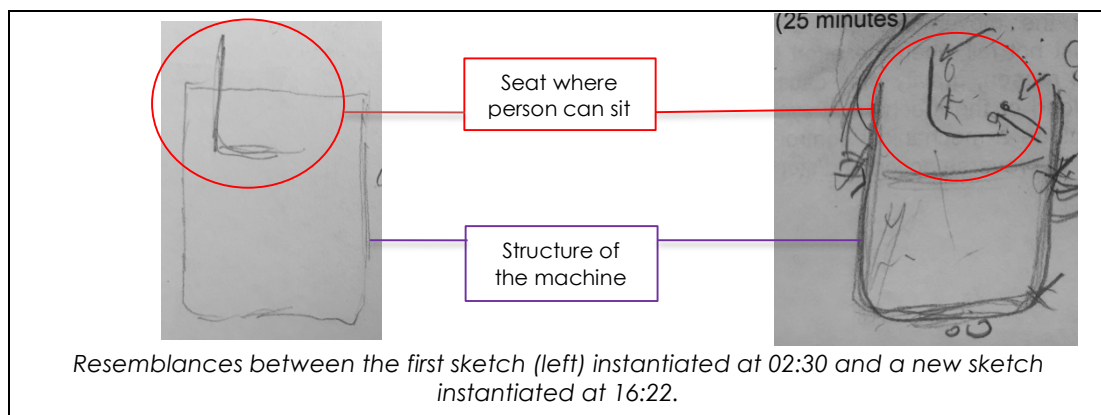


**Photograph 4.9: Preliminary design sketch generated by Group B (02:30)**

When one looks at Excerpt 4.14 and the preliminary sketch in Photograph 4.9, it seems as if Group B's problem solving phase was initiated when P3 perceived external pictorial information about a hydraulic crane and subsequently started to draw the structure of their solution based on her memory. However, since P3 interrupted the problem solving process by suggesting that they should start with the 'questions', it was unclear how P4 transformed the perceived pictorial information.

One significant difference in Group B was that they started their design process by perceiving pictorial information. This was in contrast with Group A and Group C (see section 4.4.1.c), who used internal information contained in the design task instructions to start their design process. Another significant difference was in the way Group B's participants immediately engaged in problem solving rather than problem structuring when initiating the design process.

Participants in Group B still continued with their proposed idea of a hydraulic crane later in their design process. They created a new sketch which resembled the first sketch in Photograph 4.9. The resemblance between the older sketch and new sketch is shown in Photograph 4.10.



**Photograph 4.10: New preliminary sketch of design solution based on an older sketch (shown in Photograph 4.9)**

Photograph 4.10 shows how the participants created a new sketch of an older sketch. As such, it seemed as if the older sketch instantiated during 02:30 triggered the new sketch during 16:22. Therefore, it seemed as if the participants used their sketch as a source of information when creating a preliminary design solution. Prior to initiating the new sketch, the participants investigated existing solutions to address their design problem. As such, it seemed as if the level of detail in their preliminary solution transformed. This transformation is evident in the concurrent verbalisation that P3 made while sketching the new preliminary sketch, shown in Excerpt 4.16.

#### Excerpt 4.16

**P3 16:22**

*Like to have a cylinder. The control cab will be a cylinder, then the person will be able to sit in the middle. This is the seat, the person will be here controlling, then. Gears, gears or maybe or on the steering wheel will be maybe buttons in the middle*

Excerpt 4.16 and Photograph 4.10 demonstrate how the participants of Group B transformed a previous preliminary sketch occurring at 02:30 by using it as an external source of information when solving a design problem during 16:22. The transformation was evident in the level of detail P3 provided while drawing the new sketch. The level of detail was evident when P3 specified (1) a cylindrical shape; (2) the place where a person would sit as a seat; (3) a description of the structure as a control cab; and (4) control mechanisms as gears and buttons. Therefore it seemed as if the first sketch provided the participants with information that could be transformed by adding and elaborating on detail in the new sketch. By adding and elaborating on detail in the new sketch, the participants engaged in a problem solving phase in order to provide a design specification for their design solution.

An example where the participants recalled internal information from their memory to clarify their design idea is evidenced in Excerpt 4.17. Again, the preliminary sketch afforded participants the opportunity to add detail and elaborate on a design specification.

#### Excerpt 4.17

**P3 22:20**

*The crane must come from the back or the front. I am not sure. Or must be maybe connected at the back ja. Then it goes up, right up*

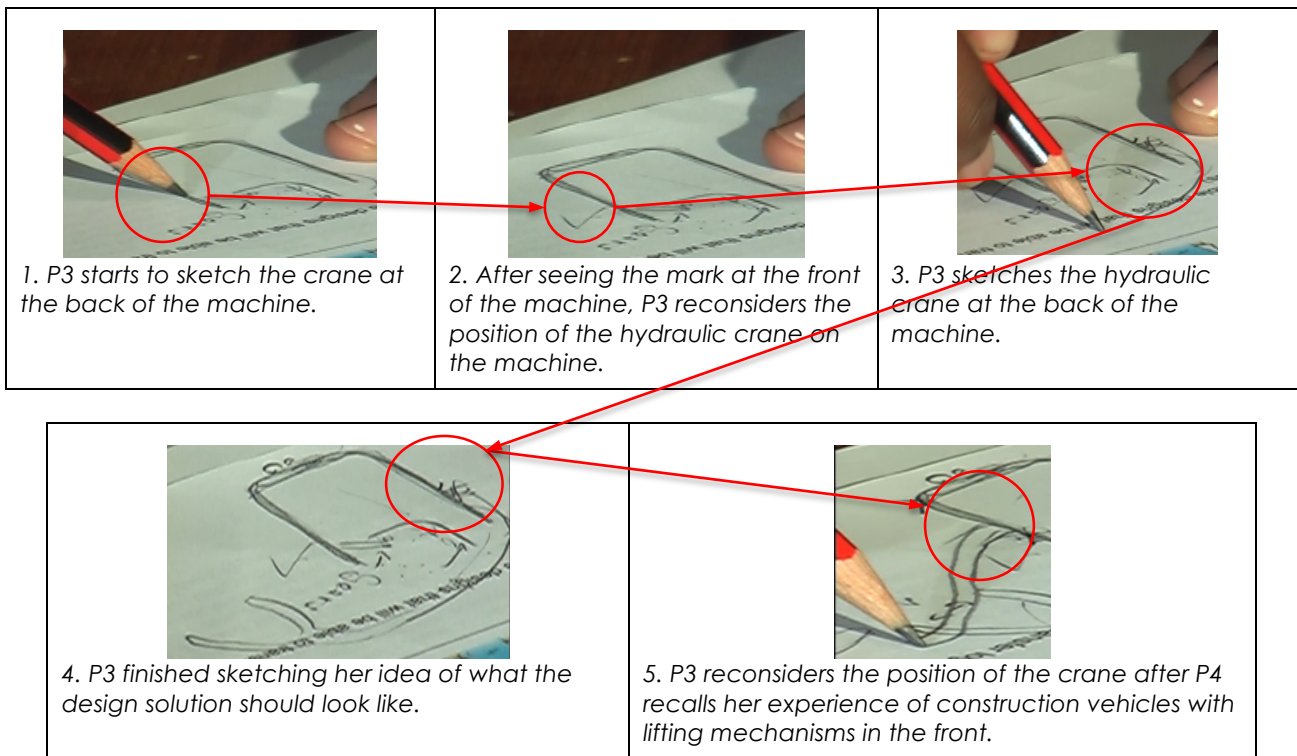
**P4 22:35**

*And it picks up the logs*

**P4 24:58**

*Cause there's a construction happening. They use this kind of things. They don't put the, what do you call it? At the back. It's at the front. So when they pick up the logs and everything, I see it's much easier, because it's in the front, not at the back.*

Prior to the instance reflected in Excerpt 4.17, the participants followed the third design task instruction to 'Suggest at least two possible designs that will be able to transfer logs from the ground on the truck'. Subsequently, they started sketching their first preliminary design based on the first preliminary sketch, instantiated at 02:30. During their preliminary sketching, ideas about the design solution developed incrementally, shown in Photograph 4.11.



**Photograph 4.11: Sequence of sketch transformation**

Excerpt 4.17 and Photograph 4.11 show how Group B's thoughts about their design solution developed in terms of clarity. This implies that the participants' understanding of their design solution was transformed from a vague idea into a clear description of where the crane should be positioned. In sequence 1-4 in Photograph 4.11, it seems as if P3 was unsure about where the crane should be positioned on the design solution. However, in Excerpt 4.16, P4 recalled from her previous experience in a construction environment: "Cause there's a construction happening. They use this kind of things. They don't put the, what do you call it? At the back. It's at the front. So when they pick up the logs and everything, I see it's much easier, because it's in the front, not at the back". By recalling information from her memory, P4 was able to transform Group B's understanding of the position of the crane. Subsequently, P3 changed the sketch to show their new understanding. In this way, it seems as if the participants were able to transform their initial understanding of their design solution by (1) reading internal information from the design task; (2) recalling the first preliminary sketch; (3) adding a pencil mark of the crane at the front of the machine; (4) perceiving the pencil mark in front of the machine; (5) modifying the crane to be at the back of the machine; (6) recalling previous experience of a construction environment; (8) justifying that the design would work more easily if the crane was in the front of the machine; and (9) modifying the crane to be in the front of the machine. Therefore, it appears as if the sequence in which the participants accessed and used sources of information contributed to their problem solving when they were able to sketch a description of their design solution. This preliminary sketch enhanced the participants' problem solving by helping them to clarify their design solution.

As can be seen from the various excerpts and photographs given, Group B's participants interactively accessed and used internal and external sources of information to solve the given problem in the design task. Group B predominantly used preliminary sketches throughout their design process to represent their design thinking and decisions, which were facilitated by the internal and external sources of information. In contrast to Groups A and C, Group B did not use 3D modelling to clarify their design ideas, but instead referred to external pictorial information which exhibited similar features to their design ideas.

In Section c), I discuss how Group C's participants were able to use internal and external sources of information that contributed to their design problem solving cognitive phase.

### **c) Group C – accessing and using information sources during problem solving**

In the following section, I describe instances of Group C's access and use of information sources during problem solving. Prior to the specific instance of problem solving, shown in Excerpt 4.18, Group C's participants considered the third instruction in the design task, namely to '*Suggest at least two possible designs that will be able to transfer logs from the ground onto a truck*'. In doing so, the participants evaluated existing solutions in order to find a second design solution.

#### **Excerpt 4.18**

**P6 23:21**

*Here we are looking for the second thing*

**P7 23:32**

*How about this one?*

**P5 23:45**

*And this one is situated, it's on the ground*

**P6 23:55**

*It's on a base. Ok, ja, it's much better. Ja, ja. This one.*

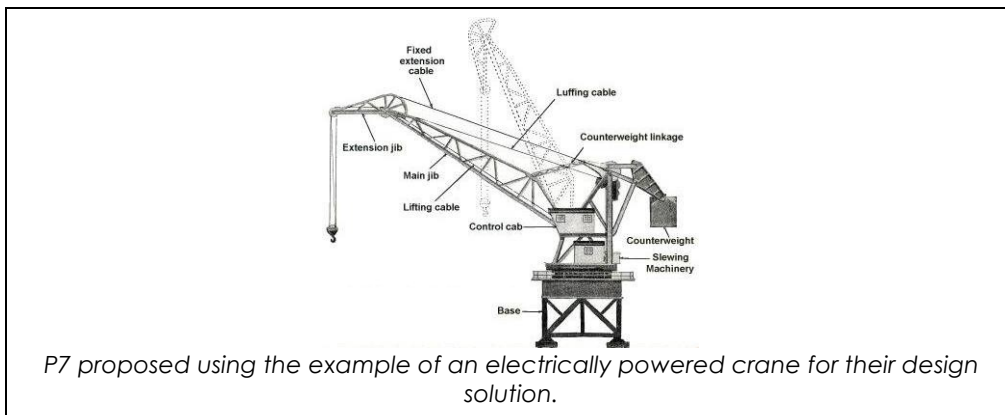
**P7 24:02**

*So it means that it should not be that far away from the truck also*

**P6 24:05**

*Ja, I think it's also ok, because as you can see, it has so many support and. Does it really need a person to? Yeah it's safe, and I think it's faster because it has height.*

Excerpt 4.18 shows how Group C's participants considered the design task instruction to select a second design solution. P7 hence proposed the electrically powered crane as a viable design solution. Group C was then able to consider the electrically powered crane by perceiving external pictorial information while they used internal information to evaluate the usability of the electrically powered crane as a design solution. The picture of the electrically powered crane is shown in Figure 4.20.



**Figure 4.20: Pictorial information of an electrically powered crane (Admin, 2011)**

Excerpt 4.18 suggests that Group C evaluated the use of the electrically powered crane, shown in Figure 4.20, as a possible design solution. By perceiving the electrically powered crane as an existing solution, the participants engaged in a dialogue in order to describe how it could be used as a solution to their problem. P5 was able to comment that the electrically powered crane is a fixed machine situated on the ground. P6 responded by commenting that the machine is on a supported base, which might be better than other solutions. P7 subsequently responded that the crane should be used near the transport trucks. It seems as if P7 was recalling a design constraint related to the topography of the logging environment from a previous problem structuring instance during 02:27 (Excerpt 4.6). This design constraint entailed the presence of a hill in the logging environment, which meant that the truck and the machine needed to be in the same place. By recalling the design constraint, P7 was able to qualify the electrically powered crane as a usable design solution. Furthermore, P6 qualified the crane as a usable design solution based on three internal design requirements from the design task. P6 evaluated the structure of the crane and paid attention to the support and stability that the base provides the machine so that it will not topple over. Secondly, P6 qualified the crane by recalling that the design solution should be safe. Thirdly, P6 qualified the crane by recalling that the design solution should make the work go faster.

It seemed therefore as if the participants in Group C were able to transform their understanding of a possible design solution by (1) reading internal information from the design task; (2) perceiving pictorial information about an electrically powered crane; (3) commenting that the crane is fixed and supported; (4) recalling a design constraint about the topography of the logging environment; (5) qualifying the crane as a usable solution because it can be situated next to the transport truck; (6) qualifying the crane as a usable solution due to an internal design requirement (stability); (7) qualifying the crane as a usable solution based on an internal design requirement (safety); and (8) qualifying the crane as a usable solution in light of an internal design requirement (efficiency).

Therefore, it seems as if the sequence in which the participants accessed external and internal sources of information contributed to their qualification of the electrically powered crane as a possible design solution. The way in which the participants engaged with information sources seems to indicate that they were finding solutions during a problem solving phase.

However, after Group C qualified the electrically powered crane as a possible design solution, P7 perceived a limitation in the design of the crane. Excerpt 4.19 shows the dialogue between the participants when P7 noticed this design limitation.

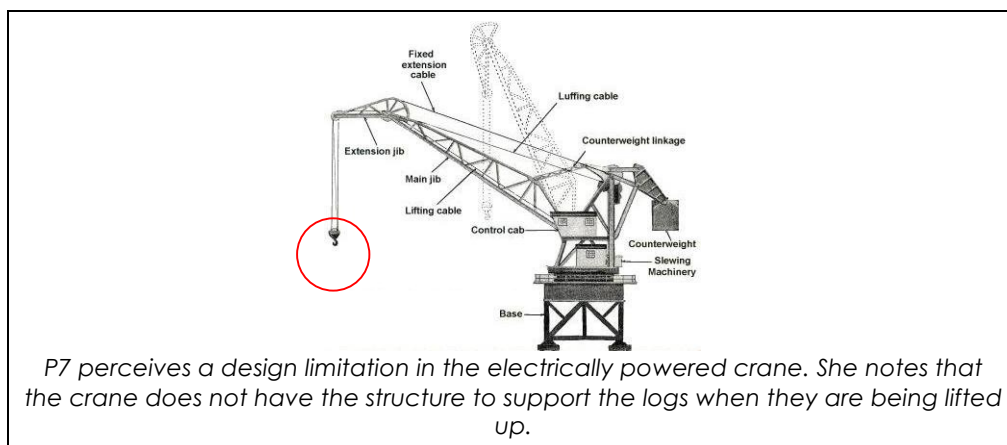
#### Excerpt 4.19

**P7 24:55**

*But wait, if we use this one, do we really. What can we use to put the logs on? Cause we have to have something. Where the logs will be put in. Then this thing will support the thing that will be holding the logs in. Cause its, it can't hold the log. Not even try to do. It has to have something like*

In Excerpt 4.19, P7 perceived a limitation of the electrically powered crane, based on a recalled design requirement from instructions in the design task. This design requirement entailed that the participants should specify 'the mechanism enabling workers to pick up and hold the logs'.

Figure 4.21 illustrates which part of the crane in the picture P7 paid attention to when she identified the limitation and subsequently recalled the internal design requirement.



**Figure 4.21: Pictorial information of an electrically powered crane (Admin, 2011)**

While P7 perceived the limitation of the crane, shown in Figure 4.21, to pick up and hold logs, she and P6 immediately searched and found pictorial information that might address the design limitation. It seems as if P7's perception of pictorial information triggered her recall of the design requirement to specify 'the mechanism enabling workers to pick up and hold the logs'. Their search for additional information to address this requirement and the perceived design limitation are shown in Excerpt 4.20.

### Excerpt 4.20

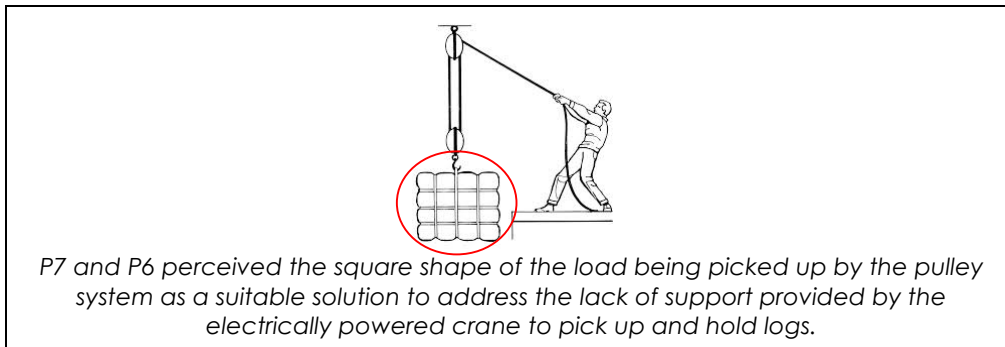
**P6 25:20**

*Yeah but. Like this?*

**P7 25:24**

*Like this one. If we want to use this one, we must put the logs in something like this.*

Excerpt 4.20 demonstrates how P6 and P7 immediately searched and found information that might address the design limitation recalled in Excerpt 4.18. They identified a square-shaped load being picked up by a pulley system in Figure 4.22 as a possible way to pick up and hold the logs.



**Figure 4.22: Pictorial information of a pulley system (The Mighty Quill, 2014)**

Figure 4.22 shows the pictorial information that P6 and P7 accessed to address the design limitation, which was recalled in Excerpt 4.18. Subsequently, P7 perceived and proposed that the square-shaped load in Figure 4.22 could be modified to pick up and hold logs. As such, it seems as if P7 could transform the ill-structured requirement to specify 'the mechanism enabling workers to pick up and hold the logs' by specifying a shape, which was perceived from the pictorial information.

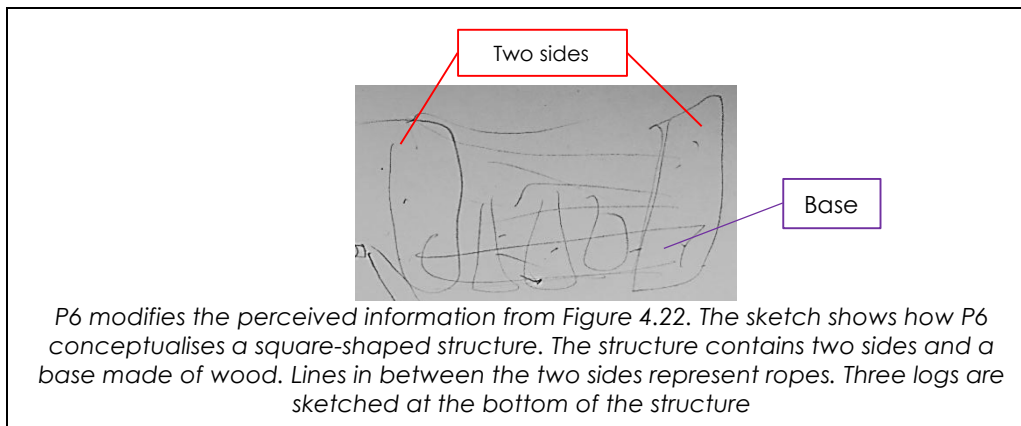
Excerpt 4.21 shows how P6 used the information perceived in Figure 4.22 and transformed it during sketching with the purpose of addressing the design limitation of the electrically powered crane.

### Excerpt 4.21

**P6 25:44**

*Like ok, only on two sides we can we can put the wood like maybe it's a base right? And then we put the logs on top and then this side we will only put the wood right and then we know that which side? Then here we can put ropes and that other side*

In Excerpt 4.21, P6 starts to transform the information that was perceived in Figure 4.22 in order to address the design limitation perceived in Excerpt 4.18. P6 conceptualises a structure that can pick up and hold the logs by sketching her idea for Group C. The sketch P6 used to communicate her idea for the structure is shown in Photograph 4.12.



**Photograph 4.12: Sketch of a structure to hold and lift logs (25:44)**

Photograph 4.12 shows the sketch that P6 made of a container in which logs could be held and picked up. This sketch developed as a result of (1) a perceived design limitation of an electrically powered crane (Figure 4.21); (2) the recalled design requirement to specify '*the mechanism enabling workers to pick up and hold the logs*'; and (3) the perceived shape of a container to hold and lift logs. It seems as if Group C was in the process of transforming an ill-structured design requirement when P6 specified a structure that could pick up and hold logs. The provision of this specification indicates that Group C's participants were busy with problem solving.

However, while P6 was sketching and specifying the structure that she was sketching, she also started to question the feasibility of her idea. This evaluation is evident in Excerpt 4.22. Questioning the feasibility of her idea led to yet another transformation.

#### **Excerpt 4.22**

**P6 26:06**

*Ja, ne, and so. But how are we going to put? If we put ropes how are we going to put the logs. Or we can actually put the logs first then I don't know, maybe put holes and then try a I don't know. Ja it's going to be difficult*

In Excerpt 4.22, P6 evaluates her sketch, shown in Photograph 4.12, by questioning how the structure will function to hold the logs. This implies that P6 recalled the internal design requirement from the design task, namely, to specify '*the mechanism enabling workers to pick up and hold the logs*' in order to evaluate her sketch. The effect of this evaluation seemed to imply that the participants needed more information about the structure that would hold and lift the logs. Group C therefore searched for more pictorial information to address their question. Excerpt 4.23 and Figure 4.23 show how P7 perceived a limitation of the sketch, which led her to search for more pictorial information.

### Excerpt 4.23

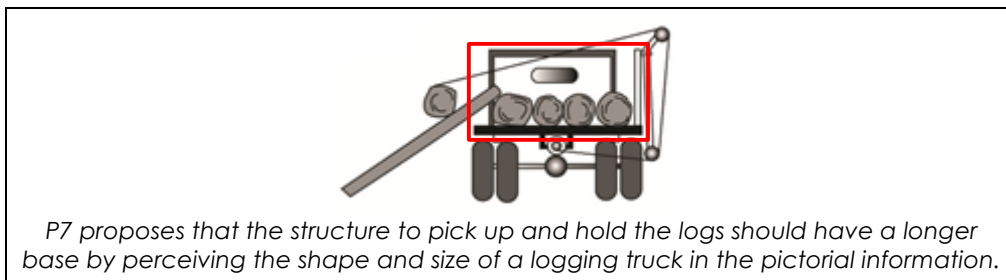
**P7 26:45**

*Because, it just needs a longer base and then on the sides we also need something strong. Then, something like this but then only if these sides were longer to support ya*

**P6 27:01**

*And thicker*

While evaluating the sketch, shown in Photograph 4.12, P7 perceived that the structure needed a longer base to pick up and hold the logs. In Excerpt 4.23, she identified this limitation, which led her to perceive another picture, illustrated in Figure 4.23, for more information. While perceiving Figure 4.23, she identified yet another limitation.



**Figure 4.23: Pictorial information about manual loading practices (Poschen, 2011)**

Figure 4.23 shows the size of the base of a logging truck, which P7 perceived to search for more information. It seems as if P7 perceived Figure 4.23 in terms of the size of the base. However, P7 immediately identified another limitation when she perceived that there were no sides to support and hold the logs. Perceiving this limitation led P7 to identify another picture to address this limitation. Excerpt 4.24 demonstrates how P7 perceived useful information in pictorial information of a gantry crane.

### Excerpt 4.24

**P7 27:10**

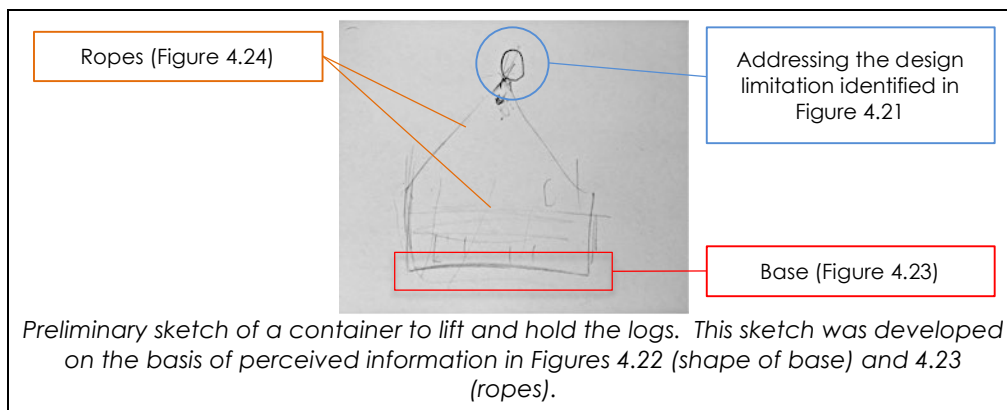
*Then, as you say, we can use the ropes; we may put them on the sides like this thing*

Excerpt 4.23 reveals how P7 perceived useful information in the pictorial information about a gantry crane. Specifically, P7 perceived ropes that could support and hold a load that is being picked up. Figure 4.24 illustrates the pictorial information that P7 perceived.



**Figure 4.24: Pictorial information of a gantry crane (Allbiz, 2010)**

By perceiving the ropes shown in Figure 4.24, which support and hold a load being picked up by a gantry crane, P7 was led to find usable information. P7 then used this information to address a limitation, perceived as the lack of support for holding logs in Figure 4.23. In this way, P7 transformed the ill-structured design requirement to specify a mechanism that could pick up and hold logs. This transformation was evident when Group C (1) perceived a limitation in their sketch (Photograph 4.11) based on a recalled design requirement to specify a mechanism to pick up and hold the logs; (2) perceived the size of the base of a logging truck (Figure 4.23); (3) perceived a limitation based on the lack of support for lifting and holding logs; (4) perceived how ropes support a load lifted by a gantry crane; and (5) added information to address the limitation identified in their sketch. The result of their transformation was later evidenced in a preliminary sketch that P7 made to show how they could address the design limitation. This preliminary sketch is shown in Photograph 4.13.



**Photograph 4.13: Evidence of used information sources in a preliminary sketch**

In Photograph 4.12, it is evident how Group C transformed information in order to address a design requirement, namely, specifying a mechanism to hold and pick up logs from the ground and convey them to the truck. Earlier, the participants had already opted to use the electrically powered crane (Excerpt 4.17). However, they were still unsure how to hold the logs while the electrically powered crane picked them up (Excerpt 4.18). Subsequently, they accessed and used various information sources to find a suitable structure in order to pick up and hold the logs (Excerpts 4.19-4.23). In this way, they were able to transform these information sources in order to develop a specification for a structure to pick up and hold logs (Photograph 4.13). Therefore, it appears as if the participants engaged in problem solving while accessing and using various internal and external information sources to produce a design specification.

Another method which the participants of Group C followed to clarify their design idea was to use stationery for 3D modelling purposes. Prior to the 3D modelling instance, P6 perceived the sketch in Photograph 4.13 and asked “*but how does the rope be on top of the logs?*” In Excerpt 4.25, P7 describes the structure in order to show P6 and P7 how it might pick up and hold the logs.

#### Excerpt 4.25

**P6 29 47**

*Tie, Ja, I understand we tie all over the round, but how does the rope be on top of the logs.*

**P7 29:54**

*It's like a gift box.*

**P6 30:00**

*Like maybe let's say this is the base right? And this, ok you can actually take this. Ok, as you can see ok, then we put the logs*

**P5 30:06**

*And then this is the. These are the ropes*

**P7 31:11**

*You tie it like this*

**P6 31:13**

*And then we pick them up*

**P7 31:14**

*And then we are going to use this thing to pick it up*

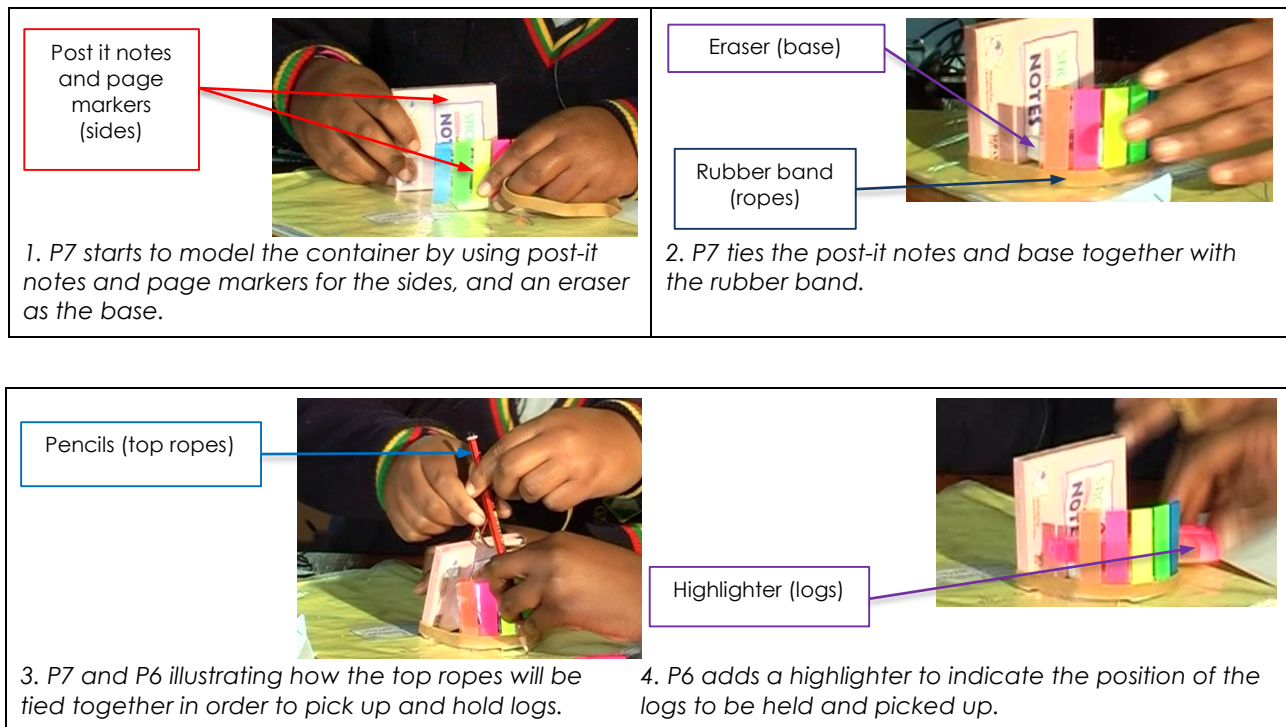
**P6 31:17**

*Oh I understand, ok right*

**P7 31:17**

*Putting the stuff in here*

P7 started by recalling from her memory to explain that the structure would work like a gift box. She was subsequently able to model the structure by using post-it notes, a rubber band, an eraser and two pencils, and a highlighter, which would hold and pick up the logs. She used the eraser to suggest the base of the structure, the page markers and post-it notes to signify the sides of the container, the rubber band to show how the ropes would tie the base and the sides together, two pencils to indicate how the ropes would be used to pick up the structure, and a highlighter to indicate logs being picked up in the container. Photograph 4.14 shows the sequence in which P7 modelled the container to pick up and hold the logs.



**Photograph 4.14: Sequence of 3D modelling**

By perceiving affordances from the stationery items in the learning environment, as suggested by Excerpt 4.23 and Photograph 4.14, the participants were able to construct a 3D model of the structure that they designed in Photograph 4.13 to pick up and hold the logs. As such, the 3D model served to scaffold their understanding of the preliminary sketch when the participants could directly perceive how the 3D structure would function to pick up and hold the logs. The transformation of the previous sketch was facilitated by (1) recalling the notion of a 'gift box' from previous experience; (2) recalling the previous sketch (Photograph 4.13); (3) perceiving the physical properties of stationery items; and (4) systematically constructing a 3D model of the container to pick up and hold the logs. In this way, the participants were able to scaffold their own understanding of how the structure that they had designed might pick up and hold the logs. Therefore, it appears as if the participants accessed and used internal and external information sources to clarify their design solution during a problem solving cognitive phase.

## 4.5 Conclusion

The aim of this chapter was to discuss the findings related to investigating the Extended Design Cognition of Grade 9 participants during a design task. I examined the verbal and visual representations produced by three groups of Grade 9 technology participants. When examining their representations, I focused on instances of the participants' problem structuring, problem solving and information access and usage behaviour. In particular, I quantitatively analysed the cognitive phases of each group of participants, as well as the information sources that they accessed and used during their design processes. Thereafter, I qualitatively interpreted and discussed how the participants accessed and used internal and external sources of information to transform their understanding of their design problem and solutions.

By viewing each group of participants' design processes from an Extended Cognition perspective, I was able to establish how internal and external information sources contributed to the design cognition of each group of participants. The extended cognition of the participants involved five levels of analysis. These levels included (1) the mode of output, (2) the content of the participants' thoughts, (3) the information sources that they accessed and used, (4) the mental operations which were applied, and (5) the cognitive phase that the participants exhibited.

In Chapter 5, I summarise my study and make final conclusions by reflecting on the research questions in terms of the conceptual framework that I used for this study. Furthermore, I reflect on the findings that I derived from studying the Grade 9 participants' design cognition from an Extended Cognition point of view.

## Chapter 5 : Conclusion and recommendations

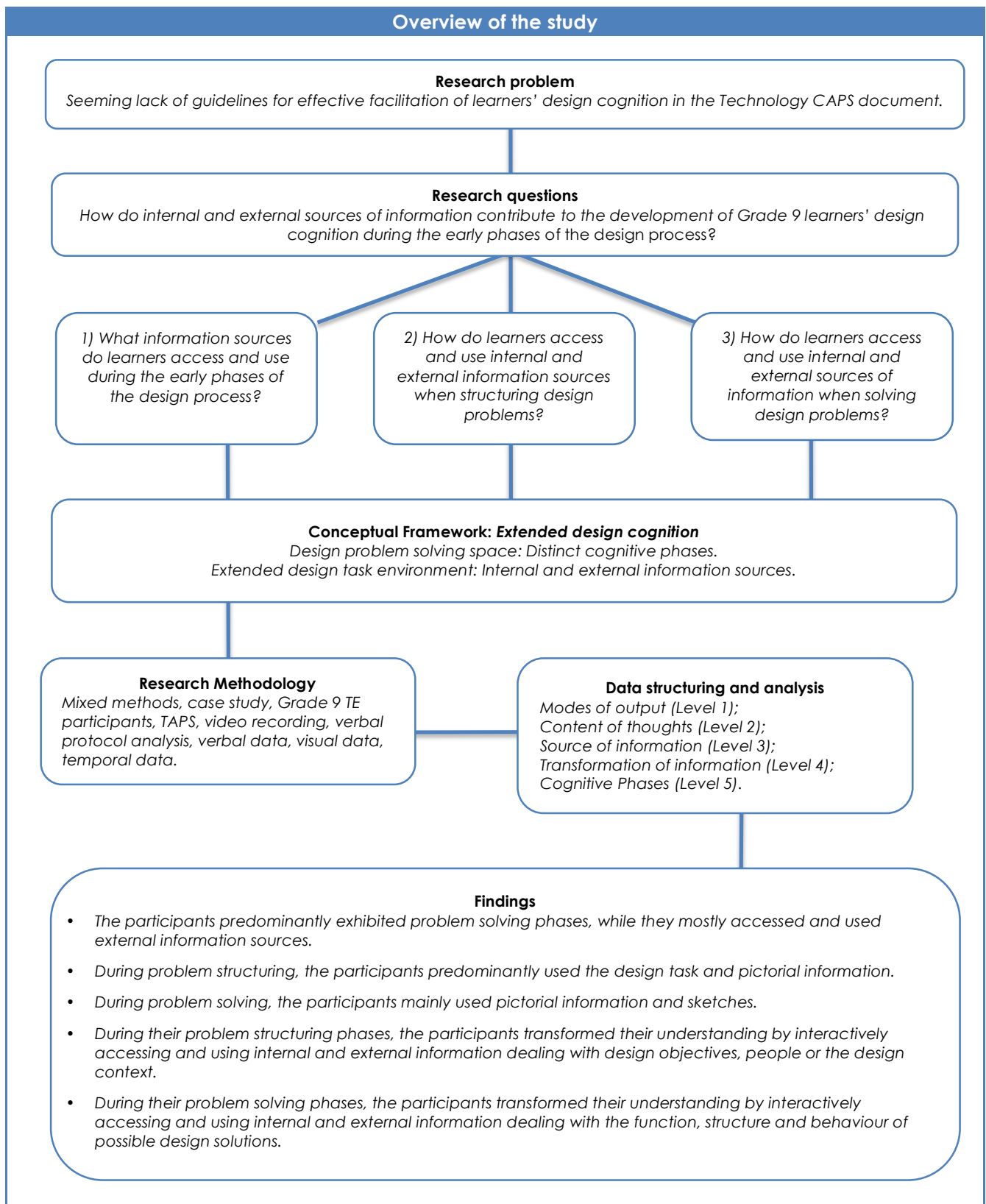
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### 5.1 Chapter overview

This chapter presents a synopsis of the preceding chapters, a summarised discussion of the way in which the research questions were addressed, and final conclusions that I reached as a result of this study. I also contextualised these conclusions in terms of what has already been found in design cognition studies. After stating the conclusions that I reached in this study, I list the potential theoretical, methodological and practical contributions that this study attempted to make. I specifically emphasise practical guidelines for technology teachers and lecturers, which was one of the aims of this study, as discussed in Chapter 1 (Section 1.6). I conclude this chapter by stating my experienced limitations and present recommendations for future research on cognition in TE.

### 5.2 Overview of the study

It has been widely recognised that designing is an information intensive cognitive activity driven by designers' ability to effectively access and utilise internal and externally located information sources (Alexiou, Zamenopoulos, Johnson, & Gilbert, 2009; Kim & Ryu, 2014; Visser, 2009). However, the CAPS document prescribed by the DoBE (2011) for technology seemingly lacks instructional guidelines to facilitate meaningful problem structuring and solving. Therefore, the purpose of this study was to investigate how the extended cognition of technology learners could be enhanced by empirically studying how the Grade 9 participants structured and solved their design problems. Figure 5.1 provides a brief overview of this study.



**Figure 5.1: Overview of the study**

The focus of this study settled on the early phases of the design process situated in a technology classroom. In particular, I investigated how internal and external sources of information contributed to the design cognition of three groups of participants during their problem structuring and problem solving activities.

The aims of this study were threefold. The first and primary aim of this study was to describe how each group of participants typically accessed and used information sources during their problem structuring and solving activities. Subsequently, I formulated the following primary research question and three sub-questions that guided the planning and implementation of my study:

***How do internal and external sources of information contribute to the development of Grade 9 learners' design cognition during the early phases of the design process?***

**Sub-question one:** *What sources of information do learners access and use during the early phases of the design process?*

**Sub-question two:** *How do learners access and use internal and external sources of information when structuring design problems?*

**Sub-question three:** *How do learners access and use internal and external sources of information when solving design problems?*

The second aim of this study was to apply an appropriate research methodology, which afforded me the opportunity to investigate and describe the naturalistic design cognition of technology learners. To this end, I adapted a conventional Think Aloud Protocol Study (TAPS), which allowed each group of participants' design cognition to be studied. I discuss the methodological contributions of this study in Section 5.5 of this chapter. By examining the moment to moment transformation of each group of participants' thoughts during problem structuring and solving, I was able to reach several conclusions.

These conclusions allowed me to address my third aim, which was to develop practical guidelines to support TE teachers in facilitating novice design cognition. I discuss these implications in terms of practical guidelines in Section 5.6 of this chapter.

At the onset of this study, I conducted a literature survey to position this study in the developing field of cognition in TE. Furthermore, I investigated the theoretical underpinnings of two prominent theories used to describe the design cognition of designers, namely, the Information Processing (Goel, 1995; Newell & Simon, 1972) and Embodiment theories (Gibson, 1986; Young, 2004). These theories have been proven useful with specific reference to how designers access and use internal and external sources of information to structure and solve their design problems. Following these two prominent theoretical frameworks, I used a conceptual framework derived from empirical studies conducted on expert designers (Haupt, 2013) to guide my methodological decisions, which in turn,

provided a roadmap to address my research questions. The conceptual framework was embedded in an Extended Cognition viewpoint and subsequently provided a sound theoretical underpinning for investigating and describing the information access and usage behaviour of the participants.

In order to collect qualitative and quantitative data that could be analysed and interpreted qualitatively, relying on Extended Cognition Theory, I applied a case study research design that was embedded in a concurrent mixed methods research approach. In order to elicit the design cognition of each group of participants, I adapted a design task from a prescribed Grade 9 technology textbook. This design task served to elicit the cognitive activities relevant to the early phases of the design process from each group of participants. Subsequently, I followed an adapted TAPS method to collect verbal and visual representations of the participants' cognitive actions during their design processes.

In my analysis and interpretation of the quantitative data, I identified the occurrences of each group of participants' cognitive phases, as well as occurrences of their information access and use. I concluded my quantitative analysis by discussing what information sources each group of participants accessed and used during their cognitive phases. In the qualitative analysis, I emphasised how participants transformed their understanding of the ill-structured design problem and its possible design solutions, by applying operators to accessed and used information sources. I discussed these transformations in terms of each group of participants' problem structuring and solving cognitive phases.

### **5.3 Conclusions in terms of the sub-research questions**

In the following section, I discuss my conclusions by relating my findings to the sub-research questions of this study. As such, I indirectly address my primary research question.

#### **5.3.1 Sub-question 1: Early phases and information sources identification**

I reflect on the contribution of my quantitative analysis to this study by discussing how the first sub-research question was addressed. This involved a discussion on frequencies and the distribution of the distinct cognitive phases, information access and use, and information access and use during each cognitive phase.

##### ***a) The distinct cognitive phases of the participants***

From an Extended Cognition viewpoint, the distinct cognitive phases characterised the purposes of the participants' information search during designing. These purposes included problem structuring and problem solving. When I counted the occurrences of the participants' cognitive phases, I found that each group of participants exhibited both problem structuring and solving behaviour, which is in accordance with studies conducted on expert design cognition. The findings indicated that all

three groups of participants spent more than 75% of their design processes on problem solving. Alternatively, less than 15% of their design processes was spent on problem structuring. This implied that the participants predominantly paid attention to finding and developing solutions rather than understanding their design problems. As such, I mainly observed instances where the groups of participants paid attention to the structure, function and behaviour of potential design solutions in contrast to finding information about the design objectives, people and context of the design problem.

Design cognition findings suggest that experts spend the majority of their time focusing on design solutions because they have previous experience with similar design problems (Goel, 1995). In contrast, novice designers tend to focus on the design problem itself, since they do not have readily available prior knowledge about the design problem to draw from (Lawson, 2005; Lawson & Dorst, 2009). Therefore, the findings of this study seem to be contradictory of the typical design behaviour of novice designers, since the participants of this study spent the majority of the time finding and developing potential design solutions. A recent large scale study (Kelley, Capobianco, & Kaluf, 2014) also conducted verbal protocol studies on High school students and found that the majority of their participants spent most of the time brainstorming solutions, whereas less time was spent on defining their design problem. As such, it seems as if further research might be necessary to investigate what high school students pay attention to during the early phases of their design processes. Furthermore, it is still unclear what the role of perceptual information is in the extended design task environment in novice design problem solving in contributing towards limited prior knowledge and experience.

I also found Leaky phases, characterised by the participants' overlapping problem structuring and solving phases (Goel, 1995; Haupt, 2013). For my study, this implied that the participants needed information about the design problem during their problem solving phases. This also implied the opposite, that during the participants' problem structuring phases, the participants started to find and develop design solutions. This idea is not a new one. Other studies (Dorst & Cross, 2001; Seitamaa-Hakkarainen, 2001) have shown that the problem space and solution space of proposed solutions co-evolve during the early phases of design processes. However, few studies in design cognition have devoted attention to the Leaky phases of novice and expert designers during their design processes, especially with regard to how information sources contribute to designers' Leaky phases. There have been some useful findings in expert design cognition that reveal the connection between Leaky phases and mental iterations (Chusilp & Jin, 2006), yet these findings are still missing in novice design cognition literature. Understanding how designers access and use information during Leaky phases might reveal how problems and solutions co-evolve during the design process.

### **b) Information source access and use of the participants**

From an Extended Cognition perspective, both internal and external sources of information are located in the design task environment. I was also able to map the different sources of information that each group of participants accessed and used during their design processes. I found that the participants mainly accessed and used external information sources. More than 75% of each group of participants' verbal utterances indicated the access and use of external information sources. This implied that the participants of this study perceived visual elements in their technology learning environment to structure and solve their design problems. The participants mainly accessed and used these visual elements from their sketches and pictorial information. Other external sources, including workbooks, and 3D modelling materials, were infrequently accessed and used. Internal sources of information were infrequently accessed and used during the participants' design processes, and included information contained in the design task such as instructions, guidelines and design objectives; and information stored in the participants' memory. Currently, little in the literature empirically reveals how designers access and use information sources (Gonçalves, Cardoso & Badke-Schaub, 2014; Restrepo, 2006). Studies seem to focus on isolated sources of information, including sketches (Goel, 1995; Goldschmidt, 1991; Suwa & Tversky, 1997) and 3D models (Khunyakari, Mehrotra, Chunawala & Natarajan, 2007; Mentzer, Huffman & Thayer, 2014). Developing empirical evidence on how novice designers find missing information from external sources might be an essential step towards supporting the efficient search for and use of information sources (Gonçalves, Cardoso & Badke-Schaub 2014).

### **c) Information access and use during the early phases of the design process**

During each group of participants' problem structuring cognitive phase, two main trends indicated that all three groups mainly used the internal information stated in the design task, as well as pictorial information about the problem context. Therefore, the participants in this study found internal information about the design problem and external pictorial information about the logging environments more useful than their memory, workbooks, sketches and 3D modelling materials to structure their design problems. As such, the participants were able to structure their design problems by finding missing information from the design task and pictorial information. Relying on these information sources was not significant, since the participants had limited experience with structuring problems set within a logging environment.

During each group of participants' problem solving cognitive phase, two prominent patterns indicated that all three groups mainly used pictorial information and their sketches as information sources during problem solving. Therefore, the participants in this study predominantly relied on external sources of information to solve their design problems. This implies that the participants did not have sufficient prior knowledge and experience to design lifting machines. As such, they accessed and used information from external sources, which contributed to their design thinking about the function, behaviour and structure of possible design solutions.

Furthermore, I found that the participants paid less attention to information sources, including prior knowledge, their workbooks, and 3D modelling materials. In this study, I did not investigate the relevance of information sources during designing, however, this finding might bring into question the types of information sources that teachers supply to learners during their design processes. This implies that the teacher should understand and predict how selected information sources could contribute to learners' design processes. Moreover, teachers might need to facilitate problem structuring or solving by focusing learners' attention on particular texts or visual information to scaffold the learners' design thinking.

From an Extended Cognition viewpoint, the participants accessed and used information in the extended design task environment. Consequently, the access and use of these information sources developed the design problem solving spaces in which the participants searched for missing information. Essentially, these findings contributed to my understanding of the types of information sources that technology learners might access and use during their problem structuring and solving activities. This holds important implications for supporting the teaching of technology.

Fundamentally, describing each group of participants' design process from an Extended Cognition viewpoint shows how design thinking is a rational activity in which information sources are purposefully and intentionally used for problem structuring and solving purposes. This implies that teachers can effectively support learners' design processes by showing and manipulating existing information sources, or by reminding learners of prior knowledge to structure and solve their design problems. However, based on my own experience, and research on South African technology classrooms (Mathumbu, Rauscher, & Braun, 2014), design tasks are generally facilitated without consideration of higher order thinking skills. This observation is also substantiated by empirical research, which indicates the lack of trained technology educators in South Africa (Mapotse, 2015; Pool, Reitsma & Mentz, 2013; Williams & Gumbo, 2012). By drawing on empirical studies, the limited understanding of design as an information intensive activity becomes evident in the South African context. The findings of this study may therefore contribute to supporting higher-order design thinking skills during technology learners' design processes.

### 5.3.2 Sub-question 2: Access and use of information sources during problem structuring

Based on the Extended Cognition framework of this study, I found evidence of the participants' access and use of internal and external sources of information to structure their design problems. This meant that while the participants were engaged in the design process, I could trace how they used information sources to transform their understanding of the design problem and its potential solutions. These tracings were based on an interdependent five level analysis (see Section 3.7) in which I determined (1) the mode of output, (2) the content of the participants' thoughts, (3) the source of information accessed, (4) the operator applied, and (5) the cognitive phase, which was evidenced.

During their problem structuring activities, the participants accessed information about the users' needs, the design context, and design objectives by perceiving and recognising useful information in the design task instructions and pictures. Information use during the problem structuring phase was evidenced when the participants transformed the information that they accessed to propose design objectives, constraints, and requirements. Accessed information was typically transformed when the participants: (1) Read/evaluated information from the design task; (2) Evaluated the problem/context; (3) Evaluated/elaborated information about the design objective; (4) Justified a design requirement; (5) Proposed/justified a design constraint; (6) Evaluated/elaborated available resources in the environment; and (7) Elaborated on the design context.

I found evidence of problem structuring activities in the participants' verbal utterances (Level 1). These utterances contained content about possible design objectives, the people involved, and the logging environment context (Level 2). During their problem structuring activities, each group of participants in this study relied on the design task as input information for access and use of internal design objectives (Level 3). In order to access the design objectives, the participants read the information contained in the design task (Level 4). Furthermore, the participants could also transform their understanding of the design objectives by evaluating the problem context perceived in the given pictorial information (Level 4). As such, the participants structured their design problem (Level 5) by proposing and elaborating on new information about the needs of people (Level 4), which subsequently resulted in their proposal of design objectives.

In addition to this, the participants were able to use elaborated design objectives (Level 3 and 4) to evaluate existing solutions (Level 4), which were accessed from the given pictorial information (Level 3), thereby initiating 'Leaky cognitive phases' (Level 5). Leaky phases originated when the content of the participants' thoughts (Level 2) addressed the structure, function and behaviour of possible design solutions, while simultaneously containing information about design objectives, the people involved and the design context. This was significant because it emphasised the iterative nature of designing, where missing information dictates the cognitive phase in which the participants engage.

By perceiving visual elements from the pictorial information (Level 3), the participants were able to find missing information when they scaffolded their design thinking by proposing design constraints and specifications, which contributed to their problem structuring cognitive phases (Level 5). Evidence of the participants' problem structuring was also found in the preliminary sketches (Level 1) that each group of participants made during their design processes.

### **5.3.3 Sub-question 3: Access and use of information sources during problem solving**

I also used the five level analyses to trace how each group of participants accessed and used information to find and develop possible design solutions.

During their problem solving phase, the participants accessed information about the function, behaviour and structure of possible design solutions by perceiving and recognising useful information in their sketches, 3D models, and pictures. Information use during problem solving was evidenced when the participants transformed accessed information to propose design specifications and limitations. Accessed information was typically transformed when the participants: (1) Evaluated existing solutions; (2) Proposed design limitations; (3) Modified existing solutions; (4) Proposed/evaluated a design idea; (5) Elaborated on a design idea; (6) Justified ideas; (7) Qualified ideas; and (8) Modified previous design ideas.

I found evidence of problem solving activities in the participants' verbal utterances and visual modes of output (Level 1). The participants' verbal outputs contained content about the function, behaviour and structure of possible design solutions (Level 2). During their problem solving activities, I found that the participants of this study primarily relied on the design task as input information during their problem solving phases (Level 3). By accessing design objectives that originated from their design task, the participants were able to perceive the structure, function and behaviour of existing solutions in the pictorial information (Level 3).

As such, the participants transformed their understanding of possible design solutions by proposing and elaborating on new information about their own design ideas (Level 4). Proposing and elaborating on possible design solutions reflected their problem solving phases (Level 5).

Furthermore, the participants were able to evaluate the behaviour and structure of existing solutions (Level 2 and 4), which were accessed through the pictorial information (Level 3), by using their internal design objectives, thereby initiating 'Leaky cognitive phases' (Level 5). Exhibiting Leaky phases during problem solving revealed how the participants needed to find missing information about their design problem in order to propose possible solutions.

The indications from the participants' problem solving phases were also found in the participants' visual outputs (Level 1). These visual outputs represented content related to the function, behaviour and structure of possible design solutions. By constantly perceiving the lines that they sketched to represent the structure of possible design solutions (Level 3), they were able to transform their understanding when they evaluated, modified and proposed their own design solutions (Level 4). 3D modelling materials (Level 3) were also used with the same operators (Level 4); however, these were used less frequently than sketches.

For technology, these findings imply that explicit focus should be placed on the verbal and visual modes of output (Level 1) that learners make during their design processes. Firstly, these modes of output can reveal what learners are thinking about while they are designing (Level 2). By understanding what learners are thinking about, teachers might be able to scaffold missing information by focusing learners' attention onto a variety of internal and external information sources (Level 3). However, these information sources need to be transformed in order to be useful during the design process. As such, teachers might need to formulate questions, or ask learners to discuss, sketch, or make 3D models of aspects of the design problem and possible solutions, which are found in specific information sources. These proposed activities could therefore stimulate the transformations of learners' understanding (Level 4) during the cognitive phases of problem structuring and solving (Level 5).

## **5.4 Summary of contributions**

### **5.4.1 Theoretical contribution**

The theoretical significance of this study contributes to the limited research that has been conducted on cognition in TE (Petrina, 2010; Middleton, 2010; Zuga, 2004). Theoretically, this study contributes to the body of knowledge on novice design cognition in two ways. Firstly, this study suggests a hybrid framework for studying the information access and use of technology learners from an Extended Cognition perspective (Haupt, 2013).

Perini et al. (2008) encourage researchers in TE to consider studying how learners design from multiple theoretical viewpoints. As such, the Extended Cognition Theory afforded me the opportunity to investigate how Grade 9 learners design from both the Information Processing and Embodiment viewpoints. By studying designing from an Extended Cognition point of view, I was able to highlight how the participants' accessed and used internal and external information sources to systematically transform their understanding of the design problem and possible solutions.

Secondly, based on several scholars in design education (De Vries, 2005; Oxman, 2001; Haupt, 2014) that have echoed the need to base educational programmes in design education on the practice of expert designers, I applied an adapted version of Haupt's (2013) Extended Cognition framework, which she used to investigate expert design cognition. This framework allowed me to trace how technology learners engaged with information sources during their design processes. By using this framework, I discovered that the participants mirrored the cognitive phases of expert designers. This mirroring is substantiated by (1) the use of a framework derived from expert design cognition, and (2) data in this study which indicated that the participants in this study exhibited problem structuring and solving cognitive phases (see Chapter 4, Section 4.3.1) that are similar to the cognitive phases that expert designers exhibit (Haupt, 2013; Goel, 1995).

I also discovered that the participants relied predominantly on external sources of information, as opposed to expert designers who rely on their memory to recall previous design experiences and knowledge. This claim is substantiated by design cognition literature (Gonçalves, Cardoso, & Badke-Schaub, 2014; Kruger & Cross, 2006). This implies that learners might use external sources of information to compensate for their limited prior knowledge and experience with design problems. As such, I was able to contribute a new understanding of the relationship between expert and novice designers' design cognition.

#### **5.4.2 Methodological contribution**

In this study, I used an adapted TAPS methodology to study the way in which participants accessed and used information sources. Recent calls for empirical research on design cognition (Petrina, 2010; Middleton, 2010; Zuga, 2004) have admonished the use of surveys and interviews; and have suggested more in-depth methodologies. By conducting the TAPS method in the participants' natural technology learning environment, and enabling participants to work in groups rather than as individuals, this study could contribute to in-depth methodologies for studying novice design cognition.

Moreover, the adapted framework (Goel et al., 2013) that I used for coding and interpreting the data of this study (see Chapter 3, Section 3.7) could be used to study the extended cognition of novice designers. Design cognition researchers (Kim & Ryu, 2014; Restrepo, 2006) have acknowledged that limited research has been done to understand how novice and expert designers access and use information sources during their design processes.

## 5.5 Professional practice contribution

In the following section, I provide practical recommendations for technology teachers. These recommendations are based on the five level data structuring and coding framework that I used to analyse the verbal and visual output of the participants in this study (See Chapter 3, Section 3.7).

### **a) Mode of output (Level 1)**

Explicit focus should be given to the external representations that learners make during their designing. Evidence of information access and use, as well as the transformations thereof can be observed from learners' verbal and visual output during designing. However, I could find no guidelines in the current technology CAPS document to indicate how teachers should assess the various external representations that learners make during their design processes, based on the sources of information that they have investigated and engaged with. Additionally, I only found instances where sketches are used as the primary external representation of the early phases of the design process (DoBE 2011, p. 44). As such, this implies that other external representations, including writing, talking, and 3D modelling, are neglected for assessment purposes during the early phases of the design process. Technology teachers could specifically plan ways in which learners might engage with multiple symbol systems to showcase how they use sources of information to conceptualise design ideas. It might also be helpful for learners to produce visual diaries in which they showcase visual elements and the prior experiences from which they derived their ideas. The various modes of output that learners exhibit also provides invaluable evidence of learners' design capability. However, teachers also need to be aware of the content of the learners' thoughts while they are externalising their thoughts.

### **b) Content of thoughts (Level 2)**

When learners verbalise or visualise their thoughts, teachers should pay specific attention to the content of the participants' thoughts. Their thoughts may reflect (1) potential design objectives, (2) the needs of the people involved, (3) the design context, (4) functions of possible design solutions, (5) behaviour of possible solutions, and (6) structures of possible solutions.

Teachers may get a clear understanding of what learners are thinking about in order to introduce new content, or develop existing thoughts. Essentially, what learners think about could help teachers to understand what sources of information are being accessed and used during their design processes.

### **c) Sources of information (Level 3)**

Design processes are fundamentally embedded and facilitated by information, and should therefore be taught as such (Kim & Ryu, 2014; Cross, 2011; Restrepo & Christiaans, 2004). This means that technology teachers should continuously recognise how learners' understanding of their design problem and design ideas are embedded in accessible informational sources. Furthermore, teaching designing in the technology classroom could be enhanced if teachers themselves are acquainted with several relevant informational sources, other than textbooks, to which learners may be directed when missing information is needed.

#### ***Internal information: Memory***

In this study, the participants rarely accessed information from their memory to structure and solve their design problem. One reason for this could be the lack of information and exposure that the participants had with the problem context. Prior to the execution of the TAPS process, the participants were engaged in 10 weeks of instruction on mechanical systems and control. It seems as if the learners barely transferred the learning done in the 10 weeks' instruction into the TAPS process, and mostly relied on external sources of information. The implication for technology educators is primarily to effectively plan design tasks on what learners already know, and make learners aware of such information by asking questions and focusing their attention on specific visual elements to elicit prior knowledge. Also, technology educators can also identify gaps in learner's knowledge, which might be needed to structure and solve design problems, and to make relevant information sources available to learners in order to substitute the limited internal sources of information that they might have.

#### ***Internal information: The design task***

During this study, I found that during their ill-structured design problem solving, the participants appeared to initiate problem structuring and solving by reading the design task, which served as the input informational requirement to drive their design processes. The role of the design task in inducing problem structuring behaviour is also reflected in expert design behaviour (Lawson, 2006; Haupt, 2013; Kim, Bouchard, Omhover & Aoussat, 2010).

For technology, this implies that teachers may evaluate and adapt presented the guidelines in prescribed textbooks in order to increase the problem structuring and solving activities of learners. Teachers can increase learners' awareness of specific content by generating questions about specific content (Level 2), which in turn might facilitate learners' approach to design problems and solutions from various alternative points of view.

### **External information: Pictorial information**

Another important finding from this study reflected the role that pictorial information played in allowing participants to perceive visual elements, which contributed to the transformation of ill-structured information in the design task. Empirical studies of design experts show that they usually have vast experience and knowledge to draw from when structuring design problems in contrast to novice designers, who still have to gain such experience and knowledge (Cross, 2011). Therefore, it is in the best interest of technology learners if teachers provide the necessary external sources of information to enhance problem structuring during the early phases of the design process, since technology learners do not yet possess the necessary information to engage in design tasks.

Visual elements in pictorial information such as shape, lines, surface area, and proportion provided learners with embodied information about the design problem context, as well as possible solutions to which they were able to apply operators (Level 4). Transforming these information sources thereby contributed to the participants' understanding of the design problem and solutions. As such, this implies that teachers have opportunities to facilitate transformations by guiding learners to pay attention to specific visual elements in pictorial information.

### **External information: Workbooks**

In the technology CAPS, the DoBE stipulates that textbook writers are responsible for developing and providing resources for design contexts (DoBE, 2011, p. 30) and developing the mini-PATs (DoBE, 2011, p. 41). Therefore, it might be necessary to evaluate the relevance and adequacy of the informational content contained in the prescribed textbooks for effective problem structuring and solving. It becomes the responsibility of the teacher to provide additional informational support during design tasks that could enhance and develop learners' problem structuring and solving. technology teachers might consider asking questions including:

- Will learners be able to identify opportunities for developing their understanding of the problem context, design objectives, or needs of the end-users?
- Will learners be able to realise broader contextual issues contained in the social, economic, political, moral and natural environments in which their design problem and solution is embedded?

- Does the textbook give a variety of contextual examples of design solutions that might enable conceptual and procedural knowledge to be transferred?

### **External information: Sketches**

For this study, the sketches that the participants made played an integral role in their problem solving cognitive phases. In Chapter 4, I indicated how the participants referred to their sketches as information sources while solving their design problems. Additionally, the sketches that the participants made could be manipulated and modified as they clarified their design ideas.

In the technology CAPS document, the DoBE (2011, p. 44) recommends that learners should use sketches reflectively to generate design ideas. However, they do not specify how learners should be guided to reflectively develop new design ideas. Furthermore, it seems as if the DoBE emphasises the communicative value of sketches, in spite of the visual reasoning potential that the sketches possess.

Therefore, teachers can engage learners in critical thinking by continuously referring to earlier sketches, while requiring learners to redraw and modify their sketches based on newly accessed information. By referring to earlier sketches and modifying them, teachers could guide learners to incrementally develop their design ideas. Moreover, by using sketching as a collaborative activity, learners could contribute to each other's design ideas. Teachers' can facilitate this collaboration by emphasising the visual elements embodied in the learners' sketches.

#### **d) Operators (Level 4)**

In this study, operators, including evaluating, elaborating, proposing, modifying, justifying, reading, qualifying, requesting, repeating and commenting were key indicators of information transformation processes. Evidence of these mental operations was evident in the external representations that the participants made. Therefore it seems necessary for teachers to encourage participatory classes where these transformations need to be elicited. It remains the responsibility of the teacher to plan these transformations by formulating questions, reminding learners about prior knowledge, or focusing learners' attention on visual elements. Technology teachers should also be informed on how to guide learners' transformation processes by incorporating appropriate questioning techniques, which might stimulate effective critical thinking skills (Haupt, 2014).

Examining the various content (Level 2) in learners' external representations (Level 1), and asking transformative questions (Level 4), could therefore provide evidence of learners' critical and creative thinking. In turn, critical and creative thinking might be encouraged if learners are required to talk, write, sketch and make 3D models of ideas about their design problems and solutions thereby encouraging other learners' critical and creative thinking to develop as they respond to each other's external representations.

In this study, how learners transformed the content of their thoughts (Level 2) from information sources (Level 3) indicated the cognitive phase they are engaging with.

#### **e) Cognitive phases (Level 5)**

The findings of this study indicated that the participants predominantly engaged in problem solving rather than problem structuring cognitive phases. As such, teachers who facilitate the design process need to consider how to mediate between the problem structuring and problem solving phases.

By introducing and asking questions about content, including the design context, people's needs and wants, and the potential design objectives of design problems, teachers can facilitate learners' problem structuring phases. This means that when teachers identify instances where learners need missing information about potential design objectives, people's needs or the design context (Level 2), teachers can focus learners' attention on specific information sources (Level 3) about the content. Furthermore, by asking questions (Level 4) about prior knowledge and visual elements, teachers can facilitate problem structuring cognitive phases during learners' design processes. Problem structuring phases can be facilitated at the beginning of a design process, as well as throughout learners' design processes.

By introducing and asking questions about content, including the function, behaviour and structure of potential design solutions, teachers can facilitate learners' problem solving phases. This means that when teachers identify instances where missing or detailed information is needed about potential design solutions in terms of possible functions, behaviour or structures (Level 2), they can focus learners' attention on specific information sources (Level 3) about the content. By further asking questions (Level 4) about prior knowledge and visual elements, teachers can facilitate problem solving cognitive phases during learners' design processes. Problem solving phases can be facilitated throughout the learners' design processes to ensure that learners transform their understanding of the design problem and potential solutions simultaneously.

## **5.6 Limitations of this study**

The first limitation that I encountered was based on the prescription provided by the DoBE to not conduct research in the participating school during the participants' normal technology instructional hours. In order to create a naturalistic technology classroom environment in which to investigate the design cognition of the participants, I had to simulate a technology learning environment that contained all the sources of information that the participants were accustomed to. I therefore compensated for this possible weakness by conducting the TAPS process in the participants' usual technology classroom. The participants also had to bring their workbooks along in order to engage with the design task.

Related to the first limitation was the inability of the TAPS methodology to mirror an authentic technology classroom environment in which research could be conducted. In my preliminary investigation of technology classrooms, which did not form part of this study, I observed multiple factors such as noise levels, interruptions, and interactions with teachers and peers, which might have compromised the richness of the data being gathered. Instead, I decided to isolate groups of participants within a naturalistic technology classroom environment in order to conduct the TAPS process. I counteracted this potential weakness by video recording participants' design activities in groups. Furthermore, I adopted the role of participant-observer, in which I acted as the 'teacher' when required by learners.

A third limitation of the concurrent TAPS methodology that I utilised for collecting data was that it did not allow for participants' externalisation of every thought they had during the design task. Therefore, it was not possible for me to provide visible evidence of each thought and subsequently make inferences to account for certain design behaviour. In order to compensate for this potential limitation, I collected multiple forms of external representations, including utterances made by the participants and concurrent sketches, writings, and 3D models. These multiple data sources proved to confirm each other, thereby validating the inferences that I made.

A fourth limitation of this study related to the sample selection, which led to multiple underlying limitations of this study:

- a) The TAPS methodology was limited to a finite number of student groups. Therefore, additional data collection is needed in order to typify the design behaviour in primary schools. In addition, using small samples for TAPS seemed to resonate with other studies conducted on novice and expert designers (Haupt, 2013; Goel, 2001; Trimmingham, 2009). The reason for using small samples can be attributed to the large amount of data that is generated, which makes reporting on findings impractical.
- b) The sample selected by the technology teacher only comprised female Grade 9 participants. The sample selection criteria included participants' ability to communicate effectively, the participants' ability to work together effectively as a group, and the participants had to have above average design skills. As such, the sample criteria did not allow the teacher to discriminate between genders. Future studies could include stratified sampling criteria, which might include an equal distribution of male and female participants.

A fifth limitation is based on the data collection strategies that were limited to data produced by the learners. Data from teachers that reflect their classroom practice might provide a more comprehensive picture of how learners engage in design tasks, however, this was not the focus of my study.

## 5.7 Recommendations for future research

The research that has been conducted for this study highlights a few areas that might be beneficial and worthwhile for the TE community to pursue in future studies. I therefore recommend the following studies:

- Quasi-experimental research designs to determine what role and quality ill-structured design tasks play in the early phases of the design process.
- Case studies investigating the extended design cognition of equally distributed gender groups during design tasks.
- Exploratory quantitative studies focusing on the correlation between different groups of participants' cognitive phases and information sources.

## 5.8 Conclusion

This chapter presented a synopsis of the research study. I gave a brief overview of the study from the discussions presented in the preceding chapters. This was followed by a discussion of the findings, which addressed my research questions. The scope of contributions that might arise from these findings was given and the practical guidelines that I derived from these findings are given for implementation in technology classrooms. I concluded this chapter by discussing the potential limitations of this study and recommendations for future research.

The Extended Cognition Theory used in this study demonstrated that the participants incrementally accessed and used information sources to transform their understanding of the design problem and its potential solutions. These transformations were based on a five level analysis, which included evidence of their (1) mode of output, (2) the content of their thoughts, (3) the source of information that was accessed and used, (4) the operator applied, and (5) the cognitive phase, which was exhibited.

The purpose of this study was to understand the role of information sources during Grade 9 participants' problem structuring and solving cognitive phases. From the findings of this study, I could conclude that the participants' design cognition was enhanced by the availability of various information sources. This implies that technology teachers play a central role as information providers and mediators. If we want technology learners to develop higher order design cognition, we should encourage current and future teachers to design and provide meaningful learning environments in which learners are exposed to various information sources during their design tasks. Failure to provide adequate information sources during design tasks could inhibit the development of the proficient design skills that are recommended in the technology CAPS document.

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## Appendix A: The Design Task

Name: \_\_\_\_\_

Participant: \_\_\_\_\_

### Problem Statement

A timber company cuts down trees in a forest and uses trucks to transport the logs to a nearby sawmill. It takes very long for workers to manually load the logs onto a truck one by one. The company needs a machine that can pick up logs from the ground and transfer them onto a truck quickly and safely.

**Fig. 1: Workers carrying logs** (Uisso, 2015)



**Fig. 2: Workers loading logs unto trucks** (Jose, 2011a)



**Fig. 3: Workers carrying logs** (Jose, 2011b)



**Fig. 4: Loaded trucks with logs** (Jose, 2011c)



### Design task

**Design a model of a machine that can pick up logs from the ground and transfer them onto the transport truck. You only have to design the lifting machine, not the truck.**

Most machines consist of several mechanisms that are combined to do a task. Your model must consist of at least two sub-systems:

- One of the sub-systems must consist of one or more mechanism that give mechanical advantage, such as *levers, linkages, wheels, cams, cranks, pulleys, gears, hydraulic or pneumatic systems*.
- The other sub-system must control the movements of the machine. Safety requirements demand that a load must not fall when the effort is removed. If the lifting process is interrupted for some reason, gravity may cause the load to drop back again. This could damage the load or the mechanical system, or it may hurt people nearby. Your design must include a mechanical control system such as a *cleat, or a ratchet and pawl*, to prevent the reverse action and/stop the movement.

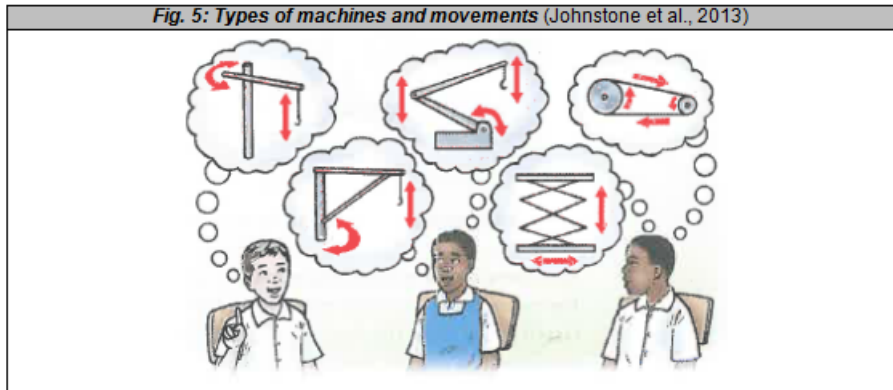
### Instructions

In this design task, you will be working in a group. You are required to design a machine that can load logs onto a truck. Throughout the design task you may use information from your memory, textbook, workbook and cell phone if you need it. You are also allowed to highlight, make notes and draw sketches on all the pictures and notes given to you.

1. Consider the environment in which the machine must function. Discuss the following questions: (15 minutes)
  - How will the environment in which the machine will operate affect its operation?
  - Will the machine always stay in the same position?
  - How high will it have to lift the logs?
  - How will you ensure that the machine will not topple over?
  - How will the machine make work quicker and faster?
  
2. Think about the movements your machine will need to perform. Which mechanisms can you use to? (20 Minutes)
  - Pick up and hold the logs
  - Lift the logs
  - Create different movement in different parts of the machine
  - Control the movements of the machine (*Gravity may cause the load to drop back and be damaged. Consider how to incorporate a control mechanism in your machine to stop this from happening*).
  - Move the machine around, if necessary

**Make as many notes of your ideas by writing and drawing rough preliminary sketches with arrows and labels to describe movements.**

*Fig. 5: Types of machines and movements* (Johnstone et al., 2013)



3. Suggest at least two possible designs that will be able to transfer logs from the ground onto a truck. (25 minutes)

**Additional information**

*Fig. 6: Workers in the logging environment (SA Forestry Magazine, 2011a)*



*Fig. 7: Team of workers for lifting logs onto trucks (SA Forestry Magazine, 2011b)*



*Fig. 8: Person packing and arranging logs on the truck (Logging on, 2009)*





**Mechanisms**

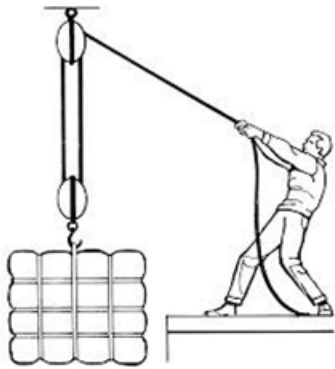
**Fig. 11: Levers** (BBC, 2014)



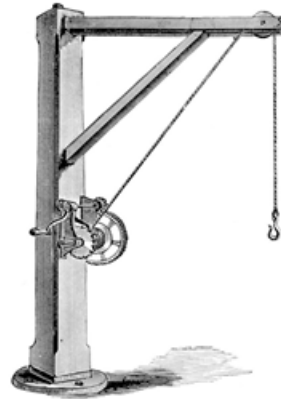
**Fig. 12: Linkages, wheel and axle and hydraulic system** (Mason & Croft, 2014)



**Fig. 13: Pulley system** (The Mighty Quill, 2014)



**Fig. 14: Gear and crank system** (Edwin Harrington, Son & Co., 2010)



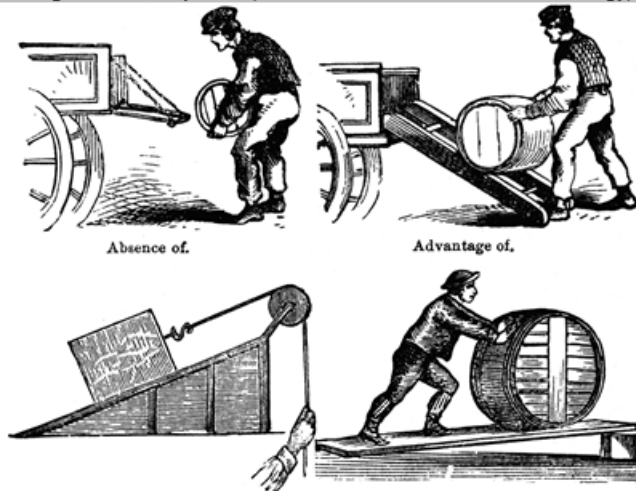
**Fig. 15: Ratchet and pawl** (Automotion components, 2012)



**Fig. 16: Cleat** (Blind technique, 2015)

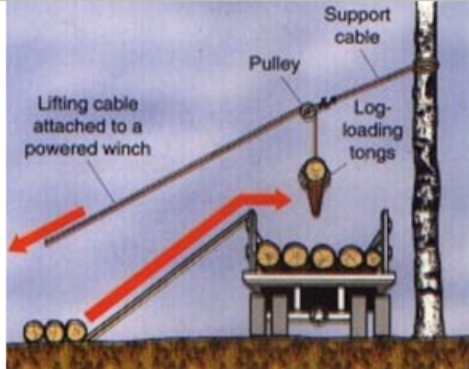


**Fig. 17: Inclined planes** (Florida Centre for Educational Technology)

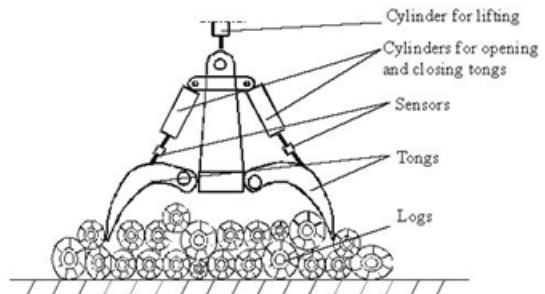


**Existing solutions**

**Fig. 19: Simple winching system** (Mostacedo, 2010)



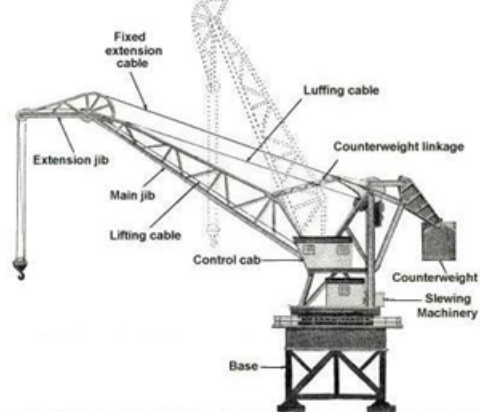
**Fig. 20: Hydraulic tongs** (Wang, LeDoux & Wang, 2005)



**Fig. 21: Hydraulic crane** (Logging on, 2009)



**Fig. 22: Electrically powered crane** (Admin, 2011)



**Fig. 23: Manual crane** (Princess Auto, 2015)



**Fig. 24: Log hauler** (Forestry Department, 1995)



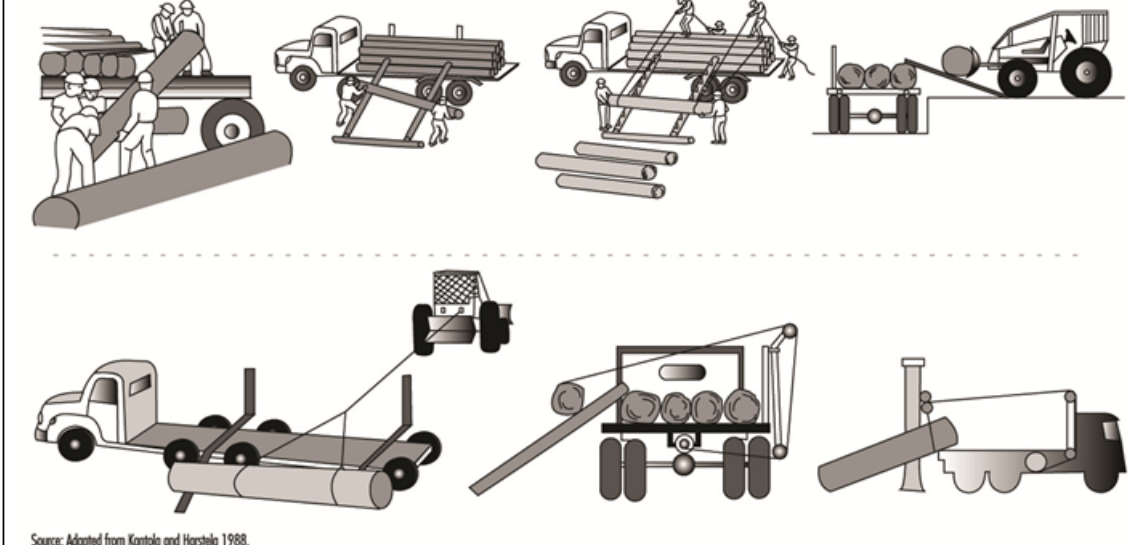
**Fig. 25: Electrically powered crane on truck** (Desertdrover, 2012)



Fig. 26: Gantry Crane (Allbiz, 2010)



Fig. 27: Manual loading practices (Poschen, 2011)



Source: Adapted from Kantola and Horstela 1988.

## Appendix B: Language editing certificate

### *Exclamation Translations*

*EXCLAMATION TRANSLATIONS*

To whom it may concern

The dissertation entitled “Extended Information processing of Technology Education learners during the early phases of the design process” was thoroughly edited and proofread as of 28 August 2015. I verify that it is ready for publication and/or public viewing as it is up to the expected standard.

*Please take note that Exclamation Translations takes no responsibility for any content added to the document after the issuing of this certificate.*

Kind regards



Melissa Labuschagne

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Melissa Labuschagne trading as Exclamation Translations.

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