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WHAT WE LEARN FROM EXPERTS ABOUT ENQUIRY WHEN WE ENGAGE IN PROBLEM SOLVING

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ABSTRACT
This paper outlines a small-scale design-based research project in progress that attempts (a) to understand the use of enquiry during the early phases of the design process from an extended cognition perspective and (b) to synthesise such enquiry behaviour with broad types of problems. The is to draw implications for engineering education curriculum design in general, and for professional development of mining engineering at the University of Pretoria in particular. The first phase of the project entails defining a suitable theoretical framework encompassing design disciplines and levels of expertise to examine and develop design behaviour. Extended cognition, approached as an information-processing system, serves as a theoretical framework. The second phase, informing the third and dominant phase discussed in this paper, comprised empirical protocol studies on expert teams from three diverse domains, namely architecture, mechanical engineering and industrial design. The methodology and results were published elsewhere and are not part of this paper. The third phase, involves the beginning of a process of mapping extended enquiry onto extended cognition and problem-solving models accepted in both engineering industry and educational contexts. Preliminary recommendations are proposed integratively for the implementation phase of the project.

Keywords: Engineering education, design cognition, enquiry, problem solving, workplace.

1 INTRODUCTION

One of the central goals of engineering education for many lecturers is to promote engineering enquiry and problem solving in students [1]. Here, enquiry is seen as the search and discovery process within the problem and solution space of the early phases of the design process experienced internally and externally by engineers. This paper aims to address some of the educational needs identified by the mining industry by reporting on the University of Pretoria's (UP) effort to attend to third-year mining engineering students preparing for their fourth-year internship. Industry indicates that, in mining engineering in particular, there seems to be an urgent need for universities to support the long journey of novices, estimated to last ten years from graduation [2:944], before the industry deems them ready for appointment to their first substantive managerial or mining project design positions [3]. The real mining environment awaiting a newly qualified mining engineer is ridden with constant physical, hence non-routine context-bound, problems related to ensuring safety, ventilation, rock engineering, mine planning, mineral resource evaluation, and mineral asset valuation [2:937, 3]. However, research indicates that engineers experience more unexpected, non-engineering problems in the workplace than the typical engineering problems they were trained to solve at university [1]. The constraints engineers experience in the workplace are often not related to engineering [1]. This requires the connection between domain specific knowledge and externally observed information emerging from the physical environment. The general approach of tertiary institutions offering engineering degrees is to engage students in two years of content and scientifically driven tasks related to fields including mathematics, chemistry, geo-sciences and physics. In accordance with the convention in engineering courses over the past six decades, the first two years of tertiary education are thus devoted to 'engineering sciences', which serve as a foundation for analytical thinking where students are required to apply scientific principles to technological problems [4]. One way of addressing this challenge is to augment third-year mining students' professional development course by exposing them to (a) a variety of enquiry tools linked to the different types of problems that engineers typically experience every day and (b) provide a model to guide lecturers and students in connecting different enquiry tools so as to develop their internal-external integrative cognitive behaviour. The purpose of this paper is twofold.

First to outline a small-scale design-based research project in progress attempting to understand the use of enquiry from an extended cognition perspective and second to connect such enquiry behaviour with broad types of problems, while aiming to draw implications for engineering education in general and for mining engineering professional development at UP in particular. The first phase of the project, outlined here, entails defining a suitable generic theoretical framework that can be applied to the early phases of the design process across disciplines and levels of expertise. Extended cognition, approached as an information-processing system of which enquiry plays a central role when solving problems, serves as a theoretical framework. The second phase comprised gaining information regarding expert design behaviour through empirical protocol studies applying mixed methodologies. The third phase, which is the dominant part of this paper, involves the initial stages of mapping of extended enquiry onto problem solving models accepted in both engineering industry and educational contexts.

2 PHASE 1: DEFINING A SUITABLE THEORETICAL FRAMEWORK

2.1 Extended cognition

One of the challenges of developing enquiry skills in design education is to foster students' independent abilities to direct their enquiry towards their own internal as well as external sources, while learning how to access and utilise relevant knowledge in ill-structured problem solving tasks [5:527]. Extended cognition is useful as it connects well with what the author regards as enquiry skills relevant to problem solving (discussed further on) and which are typically required during the early phases of the design process [6]. Internal information processing is here considered to be the internal accessing, connecting and using of stored knowledge and embodiment principles, including intention-attention and its synergistic integration with external sources and processes based on the fundamental problem solving requirement of intention [7]. Identifying engineers' intention-attention actions implies answering the question related to 'how it might be possible for designers to act on their perception'. Key to understanding how effective enquiry skills can be developed is establishing engineers' intentional reaction to perceived external clues in their environment that could provide information that would assist their problem structuring and problem solving efforts. The implication is that internal knowledge as information and embodiment principles are operating interactively. It does not fall within the scope of this paper to discuss all the potential internal and external sources of information and how the interaction functions, but these can be viewed in the original study, documented in a PhD thesis by the author [8].

Characterising *early phases* of problem solving

Rather than taking place in linear and sequential steps, problem solving is thought of here in terms of cognitive phases, as explained by Goel [7] and expanded on by the author elsewhere [6]. Two distinct cognitive phases, namely problem structuring and problem solving, are typical of the early phases of the design process. However, these two phases at times break down into a 'leaky' phase, which refer to an overlap between the phases. The notion of cognitive phase implies multiple internal and external enquiry activities from which designers, by applying their loose control structures, personal stopping rules and evaluation functions, select what should be explored, and what information should intentionally receive their attention. It is during these phases that designers' enquiry skills play a central role.

Problem structuring phase

The typical design problem in its entirety is ill-understood by engineers when they start engaging with it. This means that the information provided in the design brief is insufficient, implying that the information in this 'starting state' is insufficient. During this first phase, engineers typically attempt to understand the problem. During this phase they establish what they know and what they do not know. They enquire about people, objects and the context in which the given problem is situated [6]. As such, the notion of 'problem structuring' means that they try to understand the problem, what its scope is and what its constraints, requirements and specifications are. This phase requires designers to look for relevant information in various places – internally and externally.

Problem solving phase

The second distinct cognitive phase at issue here involves the equally complex problem solving phase. For Goel [7:97] this phase consists of three sub-phases, namely preliminary design, development and refinement. Broadly speaking, designers attempt to solve the given problem through constant enquiry about the interrelations between people, objects, and context while generating ideas, developing preliminary solutions, manipulating and transforming models [8]. They typically delay commitment and decision making in order to continue evaluating their choices in terms of functional and behavioural fitness for purpose, applying domain-specific knowledge and personal knowledge [9]. During this process they communicate their ideas in various ways including talking, writing, sketching and modelling, which they actively and concurrently use and manipulate to represent their developing thought processes. Goel [7] identified twelve psychological features prevalent during the early phases of expert designers' design process. For this paper, I consider three salient characteristics which are lacking in engineering education literature but seem to play a central role in expert design enquiry.

2.2 Salient psychological characteristics of enquiry

Three psychological characteristics, including control structures, evaluation functions and personal stopping rules are focused on here for their close cognitive association with the enquiry process. Their logical connection with critical thinking and creativity, and the implied movement between the internal and external world of engineers, necessitate an understanding of these underlying psychological mechanisms.

Control structures

A typical understanding of designers' control structures is one of looseness, which implies that expert designers have an extraordinary openness to considering multiple contexts[1]. Goel [7:92] explains that designers typically use a limited-commitment-mode control strategy that can enable them to generate and evaluate design components in multiple contexts. Closely connected to this understanding is documented evidence of designers' ability to increase their heuristic enquiry of design aspects, as they demand access to and use of alternative information sources [10, 11]. Most decisions by experts result from past experience and memory of similar cases [1].

Evaluation functions and personal stopping rules

Evaluation functions play an important role in designers' judgements of suitability while personal stopping rules represent their subjective preferences that interact with their domain specific knowledge when they enquire alternative possibilities and making decisions. These rules are bound to designers' personal beliefs, preferences and philosophical viewpoints. As there are no right or wrong answers in designing, and no real direct feedback from the world, the evaluation functions and stopping rules driving designers' enquiry are derived from their personal experience and degree of immersion in their projects. Goel [7] maintains that the questions if and when a designer considers a certain design component to be complete and whether it is a fit for purpose solution to the problem, are questions typically determined by the designer and not necessarily in line with the logic structure of the problem. These decisions are essentially founded on automatic evaluation in terms of personal preference and experience, professional standards and practice, and, ultimately, client expectations. Flexibility here helps designers to move the focus of their enquiry coherently between their own preferences and the preferred requirements of clients, which often conflict with their own, adding to the ill-structuredness of their problems [1]. By connecting these psychological characteristics with a theory of enquiry during the process of identifying, accessing and using internal and external sources of knowledge, it is possible to construct a framework that can guide the design and development of suitable learning opportunities in engineering education.

2.3 Enquiry-based reasoning

Enquiry as a form of learning is seen here as a central tool to gain information. As such, it has its origins in science education and was based on the recognition that science is essentially a question-driven, open-ended process and that students should acquire personal knowledge [12:392] when attempting to understand the fundamental nature of scientific reasoning. The argument in this paper is that by developing engineering students' connections between their psychological mechanisms in an extended task environment, we can start fostering the effective enquiry skills that are necessary to structure and solve engineering problems. It makes sense, therefore, to apply a learning theory in

[1] The converse of 'loose' control structure is 'tight structure', which is typically found under scientific experimental conditions where instructions and other aspects of laboratory control define 'boundaries' that limit the behavioural options of participants… Design experiments do not comply with these conditions, and as the boundaries provided in design briefs are insufficient and ill-structured, the control structures of designers are loose, giving them much freedom.

engineering education that assists in guiding the cognitive activities involved in enquiring tasks. For this study, I use an adaptation (Table 2) of Edelson, Gordin and Pea's [12] understanding of the cognitive function of enquiry in a problem solving context:

Table 1. Principles of enquiry, enquiry activities and their relation to extended cognition (adapted from [12:394]

Enquiry principles + Locus of enquiry + Psychological characteristics	**Cognitive activities**	**Expected links with cognitive phases**
Problematisation Internal and external enquiry. Determine gaps in information provided in start state.	Enquiry activities can lead students to discover the scope and nature of a given problem. This includes enquiry about people, objects and context relevant to the given problem.	Problem structuring phase.
Demand Internal and external enquiry as a result of insufficient information provided.	Successful completion of engineering tasks require domain-specific and generic design knowledge including conceptual, procedural, visualisation, normativity and adequacy knowledge.	Problem structuring and problem solving phase.
Discover and refine Internal and external enquiry reacting in cycles known and unknown information. Apply personal stopping rules, evaluation functions and control functions.	Pursuing answers to questions can enable students to uncover new domain-specific conceptual and procedural knowledge as well as new generic visualisation, normative and adequacy knowledge assisting their design methodology and decision making.	Problem structuring and problem solving phase.
Application Professional and personal judgment of relevance and intentions. Internal inquiry into personal stopping rules mechanising choices and decisions making.	Engineering requires application of domain-specific and generic knowledge in the pursuit of solving the given problem including conceptual, procedural, visualisation, normativity and adequacy knowledge.	Problem solving phase.

In order for these principles to be successfully learned, Edelson et al [12] suggest that lecturers consider the following suggestions for creating a suitable task environment in which enquiry can be learned:

- Enhance interest and motivation
- Provide access to information
- Allow active, manipulable representations
- Structure and guide the process with tactical and strategic scaffolding support
- Manage complexity and aid production.

These principles of enquiry and requirements for effective enquiry-based teaching could be used in a variety of ways, depending on the level of independent thinking of the class at a particular stage in their course [13] as a generic guideline to selection of particular suitable mental tools in engineering education. It is suggested that a thorough matching of such tools needs to be carried out in a scientific manner in order to establish an epistemologically authentic guideline for enquiry tasks in engineering courses. In the following section I discuss the educational implications of the afore mentioned empirical study [6] on expert design behaviour, which represents the second phase of the overall curriculum design project and informs the third phase thereof.

3 PHASE 3: RECOMMENDATIONS FOR DEVELOPING CURRICULUM

It is a well-researched fact that workplace problems are typically ill-structured [1, 7]. The notion of an ill-structured problem refers to the fact that the problem solver does not have sufficient information at the beginning of the process to know exactly where the boundaries and complexities of a given problem are. It means, moreover, that new and unexpected elements and constraints emerge during the problem solving process that render the entire problem solving process unpredictable. Design problems are typified as such kinds of problems. However, not all engineering problems are design problems. Some entail purely technical repair tasks, while others require refining or improving existing systems or artefacts. In contrast, design tasks require the planning of non-existing systems or artefacts which have never before been created and for which no known solutions or constraints therefore exist. At the heart of the categorising of problems here is the potential for unknown constraints to emerge during a process of problem solving. Whereas some problems might appear well structured at the start, constraints and unanticipated problems incrementally become apparent, which change the nature of the problems to ill-structured [1, 7]. It has furthermore been found that, within large-scale engineering refinement and design projects, multiple well-structured problems are embedded in the overall ill-structured task. However, although engineering students are used to solving well-structured problems, these kinds of problems are rare in everyday work practice. The need therefore exist mapping extended cognition, psychological characteristics and enquiry principles onto existing engineering approaches towards problem solving in order to identify learning opportunities for students that would foster their mental abilities to connect existing knowledge with information through direct observation within the boundaries of particular types of problems. In Table 2 an attempt to theoretically map enquiry into three broad categories of engineering problems is presented; this is currently being used to guide tasks in the professional development course of the said mining engineering group of students.

Table 2. Mapping enquiry tasks onto categories of engineering problems

CHARACTERISTICS ↓	**CATEGORIES OF PROBLEMS**		
	Repair	**Refine/ Improve**	**Design/ Innovate**
STRUCTURE OF PROBLEM →	Well-structured Simple	Ill-structured + well structured Complex	Ill-structured + well-structured Extremely complex
Problem space: Starting point of enquiry	Problematise: Find the faulty component; Presenting symptoms	Problematise: Existing system; Search for areas in need of improvement	Problematise: Need; Intentions; Required behaviour; Impact; Brief; Community; Environment
Focal point of enquiry	Demand: Find causes of fault; Constraints are known	Demand, discover and refine: Constraints, restraints, modification to artefact/system, interaction with people and context	Demand, discover and refine: Constraints, restraints, required structure/system, behaviour, interaction with people and context
Core reasoning process	Corrective measures: Application of known domain-specific knowledge	Analysis, evaluation & refinement: Application of known domain-specific knowledge	Design: Discover & refine unknown and known information
Sources of information	Internal domain-specific knowledge recalled from memory; External information accessed through visual perception of current problem situation	Internal domain specific knowledge recalled from memory; External information accessed through visual perception of current problem situation	Internal domain-specific knowledge recalled from memory; Internal knowledge from personal experience of similar and different problem situations; External information accessed through multiple direct perceptions of current problem situation and its constraints
Solution space: End-goal of enquiry	Put things back the way they were	Improve physical & procedural characteristics of existing systems/objects	Create something innovative; Potential for multiple unknown constraints

Sources of information	Internal domain specific knowledge recalled from memory	Internal domain specific knowledge; internal knowledge from personal experience; Internal knowledge from personal experience of similar and different solutions; External information accessed through multiple direct and indirect perceptions of current problem situation	Internal domain specific knowledge recalled from memory; Internal knowledge from personal experience of similar and different solutions; External information accessed through multiple direct and indirect perceptions of current problem situation

Table 3 presents a summary of the guidelines for lecturers for formulating suitable problems to develop the different levels of enquiry knowledge needed to solve typical engineering problems. Repair problems are not considered, and the focus is primarily on refine/improve tasks and design problems.

Table 3. Implications for engineering education to integrate extended cognition, enquiry and categories of problems

INTEGRATION	**CATEGORIES OF PROBLEMS**	
	Refine/ Improve problems	**Design/ Innovate problems**
Enquiry principle	Problematise; Demand knowledge; Discover and refine knowledge; Apply knowledge	Problematise; Demand knowledge; Discover and refine knowledge; Apply knowledge
Task environment requirement	Provide access to internal and external information in problem structuring and problem solving phase; Allow active, manipulable representations in problem structuring and problem solving phase	Provide access to internal and external information in problem structuring and problem solving phase; Allow active, manipulable representations; Structure the process tactically in problem structuring and problem solving phase; Manage complexity and aid production
Psychological characteristics expected	Control structures Evaluation functions	Control structures Evaluation functions Personal stopping rules

4 CONCLUSION

This design-research-based study outlined the first and third phase of an ongoing engineering curriculum design project. For this purpose, the first phase extended cognition is identified as a suitable theoretical framework for the project. It was shown that extended cognition implies the integration of internal and external sources of knowledge and information processing. The advantage of this framework is its ability to assist in empirically identifying typical expert design experiences during the early phases of the design process, when engaging in ill-structured problems that could be mirrored in engineering design curricula. The second phase of the project, methodology and results of an empirical study, informing the project, falls outside the scope of this paper. The author identified enquiry-based reasoning as a pedagogy suitable for fostering key psychological characteristics when applying the extended cognition framework. The implication for engineering education is therefore that lecturers should strive to identify suitable engineering problems that are sufficiently ill-structured to allow students to engage in enquiry tasks including problematisation and demanding information during the cognitive phase of problem structuring, and demanding, discovering, refining and applying information during the problem solving phase. These tasks should be sufficiently interesting and complex, be supported with access to information, allow active, manipulable representations, be structured and provide tactical guidance and enable the management of its complexity and production. It is finally recommended that the theoretical and practical opportunities for the development of psychological characteristics be further investigated. The theory of extended cognition requires empirical comparative studies determining students’ application of control structures, personal stopping rules and evaluation functions. Furthermore, a careful mapping of the epistemologically authentic enquiry into the problem solving tools typically used in engineering education including TRIZ, Kepner-Tregoe and CDIO needs to be undertaken theoretically and tested empirically.

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