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Developing knowledge for real world problem scenarios : using 3D gaming technology within a problem-based learning framework

Michael Garrett
Edith Cowan University

Edith Cowan University

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Developing Knowledge for Real World Problem Scenarios:

Using 3D Gaming Technology within a Problem-based Learning Framework

Michael Garrett

Principal Supervisor: Associate Professor Mark McMahon

Associate Supervisor: Professor Joe Luca

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USE OF THESIS

The Use of Thesis statement is not included in this version of the thesis.

Abstract

Problem-based learning is an instructional strategy that emphasises active and experiential learning through problem-solving activity. Using gaming technologies to embed this approach in a three-dimensional (3D) simulation environment provides users with a dynamic, responsive, visually engaging, and cost effective learning experience. Representing real world problems in 3D simulation environments develops knowledge and skills that are applicable to their resolution.

The Simulation, User, and Problem-based Learning (SUPL) Design Framework was developed to inform the design of learning environments which develop problem-solving knowledge for real world application. This framework identifies design factors relative to the user, the problem-solving task, and the 3D simulation environment which facilitate the transfer, development, and application of problem-solving knowledge. To assess the validity of the SUPL Design Framework, the Fires in Underground Mines Evacuation Simulator (FUMES) was developed to train mining personnel in emergency evacuation procedures at the Challenger gold mine in South Australia. Two groups of participants representing experienced and novice personnel were utilised to ascertain the effectiveness of FUMES as a training platform in this regard.

Findings demonstrated that FUMES accurately represented emergency evacuation scenarios in the Challenger mine. Participants were able to utilise existing real world knowledge in FUMES to resolve emergency evacuation problem-solving tasks and develop new knowledge. The effectiveness of the SUPL Design Framework was also demonstrated, as was the need to design learning environments to meet the learning needs of users rather than merely as static simulations of real world problems. A series of generalisable design guidelines were also established from these findings which could be applied to design problem-based learning simulations in other training contexts.

Citation

This study explored the use of 3D gaming technologies to address training and learning scenarios in the real world. This was undertaken to identify best practices for the design of interactive learning environments using problem-solving as the basis for learning activity. A 3D evacuation simulator was developed within this context to prepare mining personnel for emergency situations experienced in underground mines. Findings demonstrated that the simulator was an effective tool for familiarising mining personnel with emergency evacuation scenarios and engaging the critical thought processes necessary for survival under real world conditions. A series of broad design guidelines were also developed from these findings that can be applied to other training contexts.

Declaration

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Glossary

3D	Three-dimensional
3D environment	Computer generated environment which is depicted in three dimensions
3D simulation environment, virtual environment	A computer-generated simulation which offers a three-dimensional representation of objects and the environment
Cap lamp	A light attached to a miner's helmet for use in underground mining environments
Challenger	Underground gold mining facility located in South Australia
Decline	Primary shaft in an underground mine which descends parallel to the main ore body from which additional smaller shafts extend from to facilitate ore extraction
Depth markings	Signs painted onto the walls of underground mine shafts which identify the level of the mine in terms of depth from the surface
Escape rise	A ladder that allows underground mining personnel to climb between levels of the mine rapidly for use when access to the decline is obstructed during an emergency
FUMES	Fires in Underground Mines Evacuation Simulator
FPS	First Person Shooter, a popular type of computer game which situates gameplay within a 3D environment using a first person perspective.
Learning transfer, knowledge transfer	The application of knowledge learned in one context to another which is in some way similar.
Refuge chamber	Self-contained steel structure provided as a safe haven for underground mining personnel during an emergency which has independent power and oxygen supplies.
Self-rescuer	Portable gas mask which provides oxygen for use when there is a lack of breathable air within the mining environment
Simulation	A computer-generated representation of some real world event, system, process, scenario, or environment.
Task environment	The physical environment that can either directly or indirectly constrain or suggest different ways of solving a problem (Dunbar, 1998, p. 289)

1 Introduction

Learners can develop knowledge for real world application using computer-generated simulations which support the transfer of knowledge and skills to real world systems that are being modelled (McHaney, 1991; Towne, 1995). In this manner, learners can achieve desired learning outcomes and acquire knowledge that is necessary in the real world through a virtual environment, which situates learning in a common context and activity (Brown, Collins, & Duguid, 1989; Dobson et al., 2001).

To facilitate learning in a simulated environment, experience must be anchored in an instructional framework that guides learners in their interaction (de Jong et al., 1998; Withers, 2005). Problem-based learning is one such pedagogical framework that is consistent with the experiential and user-focussed nature of computer-generated simulation environments. Problem-based learning places an emphasis on active, transferable learning whereby learners use the problem as a focus for study of many different subjects. This actively integrates this information into a system that can be applied to the problem at hand and to subsequent and future problems (Barrows & Tamblyn, 1980). In this manner, simulation environments can be used within a problem-based learning framework to develop knowledge to address real world problem scenarios.

Advances in computer technology, increased affordability of computer technology, and the rapid growth of the Internet have facilitated the development of practical and economically feasible 3D simulation environments. These 3D environments are able to represent real world spaces realistically and more intuitively than other forms of media, and hence can be effectively used for learning and training purposes. This includes, for example, representing internal layouts of complex real world spaces for spatial awareness training, or depicting the interactions between subatomic particles to teach physics students about quantum mechanics.

The technical development of 3D environments has been heavily influenced by innovations within the gaming industry, where high consumer demand has driven rapid advancements in associated hardware and software technologies. This is particularly evident with First Person Shooter (FPS) games, where the player has a first person perspective of a 3D environment. FPS games are typically characterised as cutting edge gaming technology in terms of visual fidelity and performance, where high expectations are placed on them by the gaming public. Some

popular examples of FPS games include the Unreal Tournament, Battlefield, and Call of Duty Modern Warfare franchises.

The abilities of 3D gaming technologies (in particular the game engines used to power FPS games) have not gone unnoticed, with proponents of computer based learning recognising their potential to function as simulation learning environments. This has given rise to the serious games movement, which is directed towards the application of gaming technologies and concepts for simulation and learning purposes. Gaming technologies have been successfully used to this end in fields such as architecture, military, mining, and safety, health and medicine, cultural training, design review, and technical vocation training (Bonk & Dennen, 2005; Depledget, Stone, & Bird, 2011; Malhorta, 2002; Mantovani, Gamberini, Martinelli, & Varotto, 2001; Orr, Filigenzi, & Ruff, 2003; Schlickum, Hedman, Enochsson, Kjellin, & Fellander-Tsai, 2009; Shiratuddin & Thabet, 2011; Soflano, 2011; Zielke et al., 2009).

1.1 Significance of the Study

3D simulation environments allow users to experience real, recreated, abstract, or imaginary environments that may be too distant, costly, or hazardous to experience in the real world (Baylis, 2000). These environments grant the ability to perform actions that may not be possible, practical, safe, or ethical in the real world. 3D simulation environments provide an educational medium for developing knowledge and skills for use in real world environments. In this manner, 3D simulation environments can be designed to address specific real world learning objectives by facilitating the development and subsequent transfer of knowledge.

Simulation environments can be used to train learners via repeated exposure to real world tasks which are modelled within the virtual environment. However, for certain applications, it may be more desirable to facilitate learning that is applicable to more than just the set of specific circumstances that are depicted within the simulation environment. Problem-based learning facilitates the intentional mindful abstraction of knowledge from one context and application to another, such that a learner can develop the knowledge and skills necessary to tackle changing conditions in a given problem-solving context (Salomon & Perkins, 1989). By utilising simulation environments within this pedagogical framework, learners can familiarise themselves with representations of real world problem scenarios and develop the ability to resolve contextually similar problem scenarios within a real world environment. This approach to

training has application within industry where overcoming real world problems that are mission critical requires the development of knowledge that is applicable to more than just the immediate training context.

Real world environments may be difficult to set up for instruction, difficult to observe in operation, or may have limited suitable available time, potentially making training prohibitive (Towne, 1995). These limitations can in turn cause problems for trainees by increasing their dependence on supervisory personnel, limiting the range of operational configurations experienced, and obscuring the behaviour of the target system (Towne, 1995). 3D simulation environments offer a number of potential contributions to problem-based learning regarding the implementation of the components used to guide the learning process as well as the presentation of the problem scenario to the learner. Inexpensive gaming technologies can be used for this purpose to provide a range of complex simulations across a variety of domains. In this manner, learners can be presented with an authentic and realistic representation of a real world problem scenario together with the components necessary for the facilitation of problem-based learning integrated into a single learning environment. However, in order to ensure that real world learning objectives are satisfied, a generalisable approach to the design of such 3D simulation environments is necessary.

1.2 Research Questions

These research questions are concerned with determining characteristics for the design of 3D simulation environments that lend themselves to representing real world problem scenarios for the purposes of transferring problem-based learning.

Question 1. To what extent can a problem-based learning environment implemented using 3D gaming technologies promote learning and transfer to real world contexts?

Question 2. What design considerations are needed to support knowledge construction and transfer in a 3D, problem-based learning environment? Specifically, what design considerations are relevant to the user, the problem-solving task, and the 3D simulation environment?

1.3 Need for the Study and Proposed Approach

Conceptualising and designing a learning environment is a complex task in which a myriad of both theoretical and practical variables and outcomes need to be considered together with real world constraints (Kirkley & Kirkley, 2004). The theoretical assumptions as to how people learn must be taken into account, as must those relating to the technical implementation and presentation of learning material (Kirkley & Kirkley, 2004). Designing learning environments that support knowledge construction requires deliberate forms of planning (Oliver & Herrington, 2001, p. 77), and as such, there is a clear need for design frameworks which embrace modern technological affordances whilst also adhering to established pedagogical approaches.

This study will attempt to identify a series of design considerations which relate to the development and transfer of knowledge within 3D, problem-based learning environments. This will be explored through the identification and synthesis of design considerations from the literature, followed by the implementation of a simulator which adheres to these considerations in order to address real world training requirements. This will be explored within the context of emergency evacuation training in a real world underground mining facility using mining personnel as participants in the study. Inferences will be drawn based on their experience with the simulator with a view towards validating the design considerations synthesised from the literature and identifying generalised practices for their implementation. With this in mind, the structure of the thesis can be described as follows:

- **Chapter 2: Literature Review**
  A comprehensive review of the literature is undertaken in this chapter to provide an informed foundation for addressing the research questions proposed by this study. Design considerations necessary for supporting knowledge construction and transfer in 3D, problem-based learning environments are identified and collated together as the Simulation, User, and Problem-based Learning (SUPL) Design Framework.
- **Chapter 3: Methodology**
  The methodological approach employed during the study is described in this chapter. The Fires in Underground Mines Evacuation Simulator (FUMES) is proposed as a vehicle for evaluating the efficacy of the SUPL Design Framework and examining the effectiveness of 3D simulation environments built upon gaming technology to serve as

platforms for facilitating problem-based learning.

- **Chapter 4: Designing the 3D Simulation Environment**

  This chapter documents the design of FUMES in accordance with the SUPL Design Framework.

- **Chapter 5: Developing the 3D Simulation Environment**

  This chapter describes the technical implementation of FUMES using the DX Studio 3D game engine in accordance with the design established in Chapter 4.

- **Chapter 6: Findings – Transfer of Learning**

  The first findings chapter evaluates the effectiveness of FUMES in terms of its ability to develop knowledge for use during real world emergency evacuations at the real world mine.

- **Chapter 7: Findings – The SUPL Design Framework**

  The second findings chapter explores the effectiveness of the SUPL Design Framework in fostering learning transfer during the FUMES implementation.

- **Chapter 8: Guidelines for Implementation**

  This chapter explores the findings derived from the FUMES implementation with a view towards establishing generalised design guidelines which can be used to inform the development of 3D, problem-based learning environments using the SUPL Design Framework.

- **Chapter 9: Summary and Conclusions**

  The final chapter of the thesis summarises the findings from the FUMES implementation, acknowledges the limitations of the study, and describes how the findings can be translated for the benefit of the larger community.

Chapter 1   **Introduction**

2 Literature Review

An examination of the literature was conducted to provide a foundation for answering the research questions proposed by this study. This was undertaken to explore how 3D simulation environments could be used to develop knowledge and skills for resolving real world problems, including the design considerations that were significant in this regard.

Three key themes emerged during the exploration of the literature. Firstly, problem-based learning was reviewed to determine its suitability as a pedagogical framework within this context. This was followed by an examination of learning transfer with computer simulations in relation to developing knowledge for use in real world contexts. Finally, 3D environments were explored concerning their ability to authentically represent real world environments. These key areas were investigated to identify which design considerations contributed to problem-based learning within a computer-generated, 3D learning environment. The structure of the literature review is represented diagrammatically in Figure 2.1:
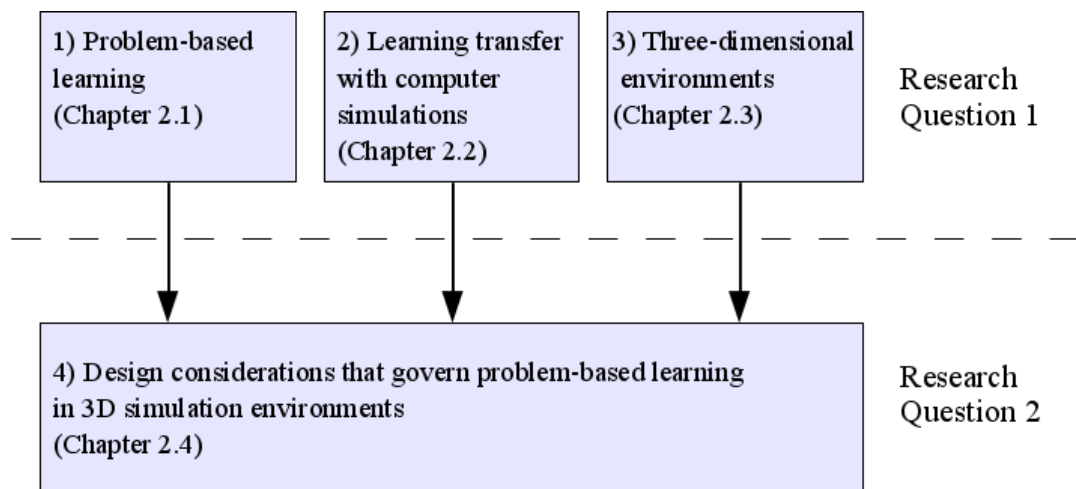
Figure 2.1. Key areas of the literature review

The following sections document the key areas of the literature review outlined in this chapter:

- Chapter 2.1 – An investigation of problem-based learning as a pedagogical framework including its learning objectives, potential benefits, and the manner in which instruction is conducted. This encompasses an analysis of the problem-solving process, which is the key component employed in problem-based learning to construct and develop

knowledge. The factors that influence the problem-solving process, both internal and external to the problem solver, also require scrutiny, as do those which affect the design and format of the problem-solving task and the manner in which learning is controlled and directed in problem-based learning environments. As this research is concerned with an individualistic approach to problem-based learning, the social and collaborative aspects of problem-based learning are not considered.

- Chapter 2.2 – An exploration of learning transfer within the domain of computer-mediated simulation environments and contemplates how knowledge that is accumulated within this type of environment can be put to use in a real world problem scenario. This includes identification and recognition of the underlying learning theories that permeate and facilitate this process. The integration of simulation environments within a problem-based learning framework as a means of providing instructional support also warrants discussion.

- Chapter 2.3 – The literature review scrutinises 3D simulation environments in terms of the characteristics which facilitate representation of real world spaces. This includes a discussion of the various technologies capable of creating 3D environments, including an examination of gaming technologies and the capabilities of FPS game engines. An in depth examination of the characteristics of FPS game engines and their potential contributions to problem-based learning will also be conducted.

- Chapter 2.4 – Finally, the factors contributing to problem-based learning in 3D simulation environments are identified, collated, and synthesised in this section of the literature review to determine the commonalities and interrelationships that exist between them. In this manner, a conceptual framework depicting the relationship between the user, the problem-solving task, and the 3D simulation environment is created. This framework identifies design considerations for supporting knowledge construction and transfer in 3D, problem-based learning environments with a view towards application in real world problem scenarios. These design considerations are highlighted throughout the literature review under headings with the key term 'summarised' in the title.

2.1 Problem-based Learning

Problems confront us on a daily basis. A significant proportion of our time, both individually and collectively as communities, is spent solving problems that can vary greatly in terms of their

complexity and the skills that are required in order to solve them. Learning these skills may involve training outside of traditional expository based teaching methods, particularly for situations where learners require deep, flexible, and transferable knowledge (de Jong et al., 1998). The need for this kind of knowledge has led to new pedagogical philosophies characterised by a constructivist epistemology (de Jong et al., 1998).

Problem-based learning is an approach to learning that is situated in problem-solving experience and is part of the classification of instructional strategies, such as anchored instruction and project-based science, that are consistent with experientially-based learning (Hmelo-Silver, 2004). Two fundamental postulates drive problem-based learning; that learning through problem-solving is more effective in the creation of bodies of knowledge usable in the future, and that problem-solving skills are more important than memory skills (Barrows & Tamblyn, 1980). Problem-based learning uses problems as the stimulus and focus for student activity and differs from other instructional methods in that it begins with problems rather than with the exposition of disciplinary knowledge (Boud & Feletti, 1997). As such, the nature and function of problems and the problem-solving process is examined in a review of the literature as follows:

- The definition and composition of a problem (Chapter 2.1.1);
- The sequence of cognitive operations that constitute the problem-solving process (Chapter 2.1.2), and;
- The factors that effect the problem-solving process (Chapter 2.1.3), including:
  - The internal factors that are specific to the problem-solver, including their existing knowledge, skills, and experience (Chapter 2.1.3.1), and;
  - The external factors that are specific to the problem-solving task in terms of the characteristics of the problem and the manner in which it is represented (Chapter 2.1.3.2).

This is followed by an exploration of problem-based learning in order to determine its suitability as an instructional strategy for developing knowledge that is applicable in real world scenarios (Hmelo-Silver, 2004; Jonassen, 2000; Mayer & Wittrock, 2006):

- Identification of the features and characteristics of problem-based learning (Chapter 2.1.4), including:
  - Examination of the educational objectives of problem-based learning (Chapter

2.1.4.1).

- Examination of the potential benefits of problem-based learning (Chapter 2.1.4.2), and;

- Understanding the sequence of stages that are used in the problem-based learning process (Chapter 2.1.4.3).

The design elements necessary for fulfilling the educational objectives of problem-based learning are also identified in order to establish design factors for the development of a 3D learning environment based on this instructional strategy (Chapter 2.1.4.4). This included design elements that are relevant to both the problem-solving task and the learning process. Finally, the combination of computer technology and problem-based learning is also investigated to determine whether the the application of computer technology within a problem-based approach to learning is complementary (Chapter 2.1.4.5).

2.1.1 The Nature of Problems

A person is confronted by a problem when he or she identifies something that they want, yet does not immediately know the series of actions required in order to get it (Newell & Simon, 1972). Problems are composed of two critical attributes: the first attribute is an unknown entity in some situation which represents the difference between the current state and the goal state, while the second pertains to the need for some social, cultural, or intellectual value in finding the unknown to be present (Jonassen, 2000). If there is no perception of an unknown, or no need to determine an unknown, then no perceived problem can exist (Jonassen, 2000).

Problem composition can be viewed as an amalgamation of three components: some starting information, a goal or desired outcome, and a method of getting from where we are to where we want to be (Johnstone, 2001). The possible permutations of these components allow problems to be classified accordingly in Table 2.1:

Table 2.1. Classification of problems (Johnstone, 2001)

Type	Data	Method	Goal
1	Complete	Familiar	Clear
2	Complete	Unfamiliar	Clear
3	Incomplete	Familiar	Clear
4	Complete	Familiar	Unclear

5	Incomplete	Unfamiliar	Clear
6	Complete	Unfamiliar	Unclear
7	Incomplete	Familiar	Unclear
8	Incomplete	Unfamiliar	Unclear

With reference to Table 1, a problem involving navigating from one familiar destination to another by car, for example, could represent a Type 1 or Type 2 problem depending on whether the problem-solver had access to a street map, which could represent a method for reaching the goal. The task environment that the problem-solver is operating in can also be considered when classifying a problem, which refers to the "physical environment that can either directly or indirectly constrain or suggest different ways of solving a problem" (Dunbar, 1998, p. 289). Recalling our navigation problem example, the task environment in this instance would comprise the outside environment including the streets that were used to navigate between the two destinations, where street signs would suggest different ways of reaching the desired destination and solving the problem.

Common amongst Jonassen (2000), Johnstone (2001), and Dunbar's (1998) composition of problems is the notion that one of the components of a problem must be missing or incomplete in order to constitute a problem. Thus, the Type 1 problem depicted in Table 1, where all problem components are complete or present, does not constitute a problem in relation to this definition. However, it should be noted that what constitutes a problem for a naive individual may not be a problem for a more sophisticated individual (Davis, 1973). This suggests that the identification and definition of problems are individually subjective (Norman, 1988). An individual who was familiar with a similar problem-solving experience to the one given, for example, would be more likely to identify the components of the problem with more certainty than an individual with no such experience.

An important distinction can be drawn between well-structured problems, where a finite number of concepts, rules, and principles are applied to a constrained problem situation (Jonassen, 2000), and ill-structured problems, where one or more problem elements are unknown or not known with any degree of confidence (Wood, 1983). Well-structured problems present all elements of the problem to the learner (Jonassen, 2000), have knowable, comprehensible solutions (Wood, 1983) and are typical of the problems presented in schools and universities (Johnstone, 2001; Jonassen, 2000). Conversely, ill-structured problems may have multiple possible solutions that are not predictable or convergent and are thus more akin to the problems

encountered in everyday and professional practice (Jonassen, 2000; Mayer & Wittrock, 2006). Ill-structured problems are consistent with those utilised in problem-based learning strategies (Hmelo-Silver, 2004) and share assumptions with constructivism and situated cognition (Hung, 2002; Jonassen, 2000). As a result, this research will focus on problems that can be classified as ill-structured to some extent.

2.1.2 Solving Problems

Problem-solving is the process of finding the unknown entities that are present within the problem situation. This process consists of a sequence of cognitive operations geared towards this goal which have two critical attributes (Jonassen, 2000):

1. The mental representation (or mental model) of the problem, which Newell & Simon (1972) refer to as the problem space and;
2. Some activity-based manipulation of the problem space.

The term *problem space* refers to the space in which problem-solving activities take place in the mind of the problem solver (Newell & Simon, 1972). This space represents the current problem situation, and includes the changes and transformations that may be possible (Dunbar, 1998). The problem space can not be pointed to and described objectively by the problem solver (Newell & Simon, 1972; Zhang, 1991), which is consistent with theories that view information as a subjective construct (Cole, 1994). The central component of these theories is the concept of knowledge structures (also referred to as mental models, cognitive models, or cognitive structures) which subjectively interpret sensory data from the outside world and transform it into information (Brookes, 1980, as cited in Cole, 1994, p. 466). As mental models are epistemic, they are not readily known to others and are not necessarily comprehended by the problem solver (Jonassen & Henning, 1999).

Whilst the meaning of problem spaces and mental models is contested (Jonassen, 2000), the types of knowledge that they contain is more clearly understood. Jonassen & Henning (1999) suggest that the internal mental models of problem spaces are composed of structural knowledge, procedural knowledge, reflective knowledge, images and metaphors of the system, and executive or strategic knowledge pertinent to the problem situation. Mental models and, in turn, problem spaces, are more than just structural maps of these components. They are multi-modal, multi-dimensional, dynamic constructs (Jonassen & Henning, 1999). Constructing a

mental model of a problem situation is an ongoing process, with the problem space changing and evolving over time (Newell & Simon, 1972):

> It need not be assumed...that the initial encoding of the stimulus will bear any close relation to the way in which it is represented internally in the subject's processing of it at some later stage. The stimulus may – and usually will – be subjected to further transformations as the subject seeks a convenient internal representation – one that he can process relatively easily. (p. 59).

The evolving nature of problem spaces corresponds with Brookes' (1980, cited in Cole, 1994) view of knowledge structures as part of an equation, whereby information is defined as that which modifies the knowledge structure from its initial state to a modified state. This suggests that knowledge structures and problem spaces are mental constructions with finite dimensions. As such, problem solvers are not presumed to have the entire problem space represented in their mind as they are solving a problem:

> Often, problem solvers will only have a small set of states of the problem space represented at any one point in time. Furthermore some problem spaces, such as that for chess, are so large that it is impossible to keep the entire space in mind (Dunbar, 1998, p. 5).

As a result of the finite dimensions of the problem space, problem solvers may not be capable of considering all possible problem states and will therefore be required to search the problem space in order to find the solution (Dunbar, 1998). problem-solving can thus be viewed as the application of methods to find a solution path amongst all possible paths that emanate from the initial and goal states within the problem space, which Newell & Simon (1972) refer to as problem trees. Problem trees can be represented graphically as per Figure 2.2. In this diagram, each circle represents a possible state, with arrows representing possible transitions between states that can be affected by applying operators. A sequence of arrows leading from the initial state to the goal state constitutes a solution path.

Figure 2.2. Graphical illustration of a problem tree, or search space (Holyoak, 1995, p. 270)

The search for a solution path involves the application of strategies or heuristics by the problem solver which allow them to move through the problem space (Dunbar, 1998). The limited ability of human beings to represent the entire problem space internally (Dunbar, 1998; Holyoak, 1995) demands that this search be guided in an intelligent manner, as an exhaustive search may not be possible. An often cited example that illustrates this point is a game of chess, where a human being cannot possibly examine all possible sequences for the duration of a game and instead concentrates on a small number of alternatives that are most likely to yield a solution. This is a heuristic search in which a 'rule of thumb' is applied that is generally thought to result in a correct solution, but does not guarantee it (Dunbar, 1998). Heuristic search methods can vary between very general methods applicable to a wide variety of problems, to much more specific methods which depend on detailed knowledge of a particular problem domain (Holyoak, 1995). A number of these heuristic search methods are summarised in Table 2.2 in order of increasing complexity (Dunbar, 1998):

Table 2.2. Heuristic search methods for selective exploration of the problem space

Search Method	Description
Random state selection	Problem solver randomly select the next state. Often used when the direction to the goal state is not known at all.

Hill climbing technique	Problem solver only examines states in the immediate vicinity to the current state and then chooses the state that most closely approximates the goal state. This strategy can be useful if it is not possible to look at more states than those just in the immediate vicinity, but it can lead problem solvers astray.
Means-ends-analysis	Problem solver examines the goal state for differences compared to the current state. If the problem solver cannot apply an operator that will get to the goal state, because the operation is blocked or cannot be executed, they set a sub-goal of removing the block, which becomes the new goal.
Analogical reasoning	Relies on the problem solver having previously solved a similar problem. In this case, the problem solver can go directly to the solution by mapping the solution to the similar problem onto the current problem. This allows the problem solver to transition between different areas of the problem space, bypassing intermediate states along the way.

The heuristic search methods detailed in Table 2.2 have the common objective of reducing the amount of exploration required to find a solution path within the problem space. The number of executions of elementary processes required to find a solution path is closely correlated with the degree of searching undertaken within the problem tree (Newell & Simon, 1972). Thus, based on the heuristic search techniques outlined in Table 2, we could expect that increasingly complex search techniques would result in a better directed and more efficient search of the problem space. As Newell & Simon (1972) argue, this is indeed the case, whereby major reductions in problem-solving effort are generally associated with heuristics that increase the selectivity of the system. However, in some cases, the increased selectivity gained as a result of a heuristic search can be almost offset by the increased processing effort that is required to produce it (Newell & Simon, 1972),. Based on these contentions, it is clear that a certain degree of expertise is required in order to select and apply an appropriate search method for a given problem space. The development of expertise necessary to this end is based largely on the acquisition of knowledge that restricts the need for extensive search (Holyoak, 1995).

2.1.3 Factors Affecting problem-solving

The capacity of a problem solver to solve problems is contingent on their ability to form a mental representation of the problem space (Jonassen, 2000) in association with their ability to search for a solution path within the problem space (Dunbar, 1998). These abilities are dependent on what the problem solver brings to the problem-solving experience, what the

problem-solver does in order to solve the problem, and the nature of the problem itself (Smith, 1988). Problem variation, problem representation (or problem type), and the individual differences of the problem solver can thus be considered as factors which affect problem-solving ability (Jonassen, 2000). These factors can be separated into internal and external categories, with distinction contingent on whether they are related to the personal characteristics of the problem solver, or the characteristics of the problem (Lee, 2004). This is consistent with the distributed nature of problem representations which are composed of both internal representations that reside within the mind of the problem solver, and external representations that exist in an external medium (Zhang, 1991):

> … the internal and external representations involved in a given problem together form a distributed representation space mapped to a single abstract problem space that represents the abstract properties of the problem. Each representation in the distributed representation space sets some constraints on the abstract problem space (p. 1).

Whilst some domains may feature a disparate emphasis between the internal and external factors that influence problem representation (Robertson, 2001), it is important to note that reliance on one type of factor does not render the influence of the other type of factor negligible (Jonassen & Henning, 1999; Robertson, 2001)

2.1.3.1 Internal Factors

Internal factors describe the individual differences between problem solvers that mediate learning to solve different kinds of problems (Jonassen, 2000). These internal factors influence the problem solver's problem representations, reasoning, searching, and development whilst engaged in problem-solving (Lee, 2004). Internal factors affecting problem-solving ability include prior knowledge, domain knowledge, structural knowledge, and the general problem-solving skills possessed by the problem solver.

Prior Knowledge

Problem solvers often call upon knowledge of previous problem-solving experiences when presented with a problem which is in someway similar. Prior knowledge serves as "the basis upon which the solver analyses the problem, reasons toward a solution, and assesses the

appropriateness of the solution achieved" (Smith, 1988, p. 6).Thus, prior knowledge is considered indispensable to the problem-solving process and one of the strongest predictors of problem-solving ability in an individual problem solver (Jonassen, 2000; Lee, 2004).

As Jonassen (2000) suggests, familiar problems are more transferable, at least within the task environment. As a result, familiar problems appear more well-structured to experienced problem solvers, with less unknown or uncertain entities within the problem domain. However, while familiarity with a problem facilitates problem-solving, the skill seldom transfers to other kinds of problems or even to the same kind of problem represented in a different manner (Jonassen, 2000). The degree and effectiveness of this transfer is contingent on the problem solver being familiar with a contextually relevant source problem that can be adapted to the current problem situation (Robertson, 2001).

Domain Knowledge

Domain knowledge refers to the realm of knowledge that individuals possess which is relevant to the particular subject area under consideration. As Alexander (1992) notes, domain knowledge can be considered as a specialised instance of an individual's prior knowledge. Knowledge of the domain is important to understanding the problem and creating solutions and, as such, a problem solver's level of domain knowledge is another strong predictor of their problem-solving performance (Jonassen, 2000). Domain knowledge encompasses declarative and procedural knowledge - explaining the what, where, when, and how of the particular area of interest (P. A. Alexander, 1992; Lee, 2004; Smith, 1988).

Declarative knowledge represents awareness of some object, event, or idea to the point where it can defined or described, but not necessarily understood (D. Jonassen, Beissner, & Yacci, 1993; Lee, 2004). Declarative knowledge is often characterised as schemas (Rumelhart & Ortony, 1977, as cited in D. Jonassen et al., 1993), which describe the means by which similar experiences are assimilated and aggregated such that they can be quickly and easily remembered (Marshall, 1995). A well-formed schema is characterised by two predominant features: the association of information in memory and the collation of various forms of knowledge (Marshall, 1995, p. vii):

> A distinctive feature of a schema is that when one piece of information
> associated with it is retrieved from memory, other pieces of information

connected to the same schema are also activated and available for mental processing. A second important feature is that many different kinds of knowledge are linked through the schema, including conceptual information, discriminating features, planning mechanisms, and procedural skills.

Utilising declarative knowledge enables problem solvers to define and know which information, or schemas, are necessary for the problem-solving task at hand (D. Jonassen et al., 1993; Lee, 2004). As Smith (1988) contends, grouping associated knowledge into schemas enhances the problem-solving process, as related procedures, conceptual knowledge, and memories of related experiences can be triggered simultaneously whilst also decreasing demands on the short term memory of the problem solver.

Procedural knowledge describes how learners use or apply their declarative knowledge (P. A. Alexander, 1992; D. Jonassen et al., 1993). Procedural knowledge mediates the relevant application of declarative knowledge whilst also supporting the problem solver to form plans, make argumentation regarding the problem-solving process, and relate the relevant information to the problem situation (Lee, 2004). This includes knowledge of the different strategies, heuristics, algorithms and the like which are relevant to the problem at hand, as well as the constraints under which they can be applied (Smith, 1988). In performing these activities, problem solvers must access and interrelate relevant schemata and extract the relevant attributes to apply to the situation (D. Jonassen et al., 1993). Through practice, these procedural knowledge schemata evolve to the point where mental activities are represented in more complex, performance-oriented schemata, which are referred to as scripts (D. Jonassen et al., 1993).

Structural Knowledge

Whilst knowledge of the domain is important to understanding problems and creating solutions, it is imperative that this knowledge is well-integrated within the mind of the problem solver in order to support the problem-solving process (Jonassen, 2000; Lee, 2004). Clearly, knowledge as to the organisation of relationships of declarative and procedural concepts is required if the problem solver is to understand the what, where, when, and how of the problem situation. To this end, structural knowledge details how concepts within the domain are interrelated and organised (Jonassen, 2000; Lee, 2004). Structural knowledge mediates the translation of declarative domain knowledge into procedural domain knowledge and enables learners to form

the connections they need in order to utilise scripts or complex schemas (D. Jonassen et al., 1993). Furthermore, structural knowledge is necessary in order for problem solvers to think about the organisation of the knowledge needed for problem-solving and its relationship with the information that is expressed in the problem (Lee, 2004).

General problem-solving Skills

Problem solvers rely on both domain specific prior knowledge as well as general problem-solving knowledge in order to solve problems (Smith, 1988). Successful problem solvers typically rely on their knowledge of general problem-solving procedures in areas in which they are not an expert (Smith, 1988). These situations are characterised by the use of less complex heuristics such as trial and error and means-ends analysis techniques in which the problem solver has no previous experience with a similar problem (Smith, 1988). This is especially true of novice problem solvers (Doolittle, 1998).

General problem-solving skills also enable problem solvers to reason which strategies may be appropriate for a given problem-solving situation (Jonassen, 2000; Smith, 1988). As such, a distinction between novice and expert problem solvers can be drawn based, in part, upon their selection of problem-solving strategies (Jonassen, 2000). Novice problem solvers use *weak* strategies which reflect their lack of previous experience with a contextually similar problem situation, such as means-ends analysis (Jonassen, 2000). Weak strategies, much like general problem-solving knowledge, are broadly applicable across a variety of domains, but are typically inefficient in ensuring the rapid achievement of an appropriate solution (Smith, 1988). Expert problem solvers, on the other hand, apply *strong,* domain-specific strategies which allow them to modify their internal problem space as more is learned about the problem (Jonassen, 2000; Smith, 1988). It should be noted however, that expert problem-solving is not identical to successful problem-solving, as novice problem solvers can learn to use strong problem-solving techniques to successfully solve problems (Smith, 1988, p. 7):

> Most experts are indeed successful problem solvers, but our research has continually identified those exceptional novice subjects who use problem-solving techniques that are very similar to those used by the experts and who can successfully solve the problems given an adequate introduction to and practice in the domain... Analysis of the performance of "successful novices" ... reveals that certain differences between their problem-solving and that of

experts in the domain. In particular these subjects are typically more informative since much less of what they know and do is tacit information as it is in the expert subject. In addition, their performance is not confounded by the extraneous variable of experience.

Internal Factors - Summarised

The individual problem solver's degree of prior knowledge, domain knowledge, structural knowledge, and general problem-solving skills are factors that affect problem-solving performance. These factors influence the development of the problem space and the subsequent strategies employed in the search for an appropriate solution path. The internal factors affecting problem-solving performance as identified in the literature review are summarised in Table 2.3 together with relevant criteria for the purposes of evaluation:

Table 2.3. Factors internal to the problem solver which affect problem-solving performance

Factor	Criteria for evaluation
Prior knowledge	· Previous experience with contextually similar problems · Identification of unknown entities in the problem · Evidence of learning transfer
Domain knowledge	· Identification of objects, events, and ideas relevant to the problem · Identification of information necessary for resolving the problem
Structural knowledge	· Identification of relationships in the problem domain
General problem-solving skills	· Reliance on general problem-solving skills · Specificity of the problem-solving strategy

2.1.3.2 External Factors

External factors describe variations in problem type and problem representation that mediate learning to solve different kinds of problems (Jonassen, 2000). External factors considered to affect problem-solving ability include the variable characteristics of the problem, including its structuredness, complexity, and domain specificity, as well as the manner in which the problem is represented to the problem solver.

Structuredness

Structuredness is the perceived value of the structure that a problem has as identified by the problem solver (Lee, 2004). Given that the structuredness of a problem can be defined along a spectrum with complete, familiar, and well-structured problems at one end, and incomplete, unfamiliar, and ill-structured problems at the other (Minsky, 1961), the degree of structuredness perceived by a problem solver is subjective and contingent on their own problem-solving skills and abilities (Taylor, 1975). These skills and abilities allow the problem solver to recognise a problem as either well-structured or ill-structured according to their identification of unknown elements in the initial state, goal state, and method(s) for reaching the goal state from the initial state.

Problem structure is a cause for distinction because well-structured and ill-structured problem-solving relies on different problem-solving skills and abilities (Jonassen, 2000). Given that well-structured problems and ill-structured problems differ according to the specification of the initial state, goal state, and allowable operators or methods (Mayer & Wittrock, 2006), it is reasonable to suppose that different attributes are required in order to locate an appropriate solution. In a study comparing the problem-solving skills required for solving well-structured and ill-structured problems in a multimedia astronomical problem-solving environment, Shin, Jonassen, and McGee (2003) concluded that solving well-structured and ill-structured problems required different component skills. They found that domain knowledge and justification skills were significant predictors of well-structured problem-solving performance, whereas ill-structured problem-solving performance was significantly predicted by domain knowledge, justification skills, science attitudes, and regulation of cognition (Shin et al., 2003). In another study investigating the effect of problem-solving characteristics on mathematical problem-solving performance, Lee (2004) discovered that students perceptions of structuredness had a positive effect on successful problem-solving performance. Students were found to be more likely to solve a given problem without difficulties if they perceived the problem as being more structured, that is, more well-structured than ill-structured (Lee, 2004). Taylor (1975) draws the distinction between solving well-structured and ill-structured problems as follows:

> The responses appropriate for solving well-structured problems involve the application of standard transformations, such as program libraries containing algorithms and heuristics. Positive transfer of previously-learned responses should facilitate solving well-structured problems.

Ill-structured problems require that the problem be reformulated in a potentially fruitful manner prior to solution. Reformulation frequently involves opening or closing problem constraints in an attempt to define or structure the problem more explicitly. The form a problem takes is important since solution strategies must be appropriate to the problem structure to be effective. (p. 28)

Complexity

Problems may vary with respect to their complexity, the degree to which the elements of a problem are interwoven and interrelated with each other (Lee, 2004), and how many, how clearly, and how reliably these elements are represented implicitly or explicitly (Jonassen, 2000). Problem solvers judge the complexity of a given problem as a consequence of the state of ambiguity and uncertainty of the context in which the problem is situated (lo Storto, 2001). Thus, the complexity of a problem is a product of the problem solver's perception and interpretation in conjunction with the manner in which it is represented to them. The most complex problems are dynamic, where the task environment and its factors change over time (Jonassen, 2000).

Task complexity is a product of any objective task attributes that increase information load, information diversity, or information rate of change (Campbell, 1988). A complex task can thus be defined as any task in which high cognitive demands are placed on the individual undertaking the task (Campbell, 1988). As summarised in Table 2.4, there are four basic task characteristics that contribute to task complexity (Campbell, 1988). These characteristics coincide with a definition of problem-solving that entails the search for a solution path between an initial state and an end state.

Table 2.4. Task characteristics used in defining task complexity

Task Characteristic	Description	Conditions
Multiple paths	An increase in the number of possible ways to arrive at a desired outcome increases information load, thus increasing complexity.	Multiple paths increase task complexity: (a) when only one path leads to goal attainment, although many paths appear as possibilities, and (b) when there is an efficiency criterion embedded in the task, and the paths are evaluated against the efficiency criterion.

		In both cases, complexity grows according to the number of paths involved. If all paths are likely to result in a desired outcome, such redundancy may actually decrease task complexity.
Multiple outcomes	As the number of desired outcomes of a task increases, complexity also increases.	If the desired outcomes are positively related, the degree of complexity is reduced. The positive relationship builds in redundancy.
Conflicting interdependence among paths	Complexity can occur because of negative relationships among desired outcomes.	If achieving one desired outcome conflicts with achieving another desired outcome, complexity will increase.
Uncertain or probabilistic linkages	Information processing requirements will increase substantially if the connection between potential path activities and desired outcomes cannot be established with certainty. Uncertainty also can increase complexity by enlarging the pool of potential paths to a desired outcome. If path possibilities are not completely bounded, then uncertainty about the existence of another, more effective path must be considered.	If probabilistic linkages exist, information load will be affected (i.e., potential paths cannot be eliminated quickly), and diversity will be affected (i.e., different action outcome contingencies must be evaluated).

The characteristics used in defining task complexity outlined in Table 2.4 suggest an overlap between the complexity and structuredness of a given task or problem, as the uncertainty associated with a problem is likely to be affected by the complexity of its individual components. Changes to the number of paths or outcomes, including the nature of the linkages between them, are likely to contribute not only to the level of complexity, but also to the level of uncertainty, and thus perceived structuredness of a given problem. Although not always the case, ill-structured problems tend to be more complex than well-structured problems, especially those that emerge within everyday practice (Campbell, 1988; Jonassen, 2000). It is important to note that distinctions between complexity and structuredness can be highlighted by the manner in which the components of the problem are represented to the problem solver (Jonassen, 2000; Lee, 2004). If the number of components and clearness of the problem are focuses of the

problem representation, then the structuredness of the problem is highlighted for the problem solver and uncertainty is reduced (Lee, 2004). When the problem solver examines the relationships amongst the components of the problem it is then that the complexity of the problem is highlighted (Lee, 2004). This is particularly true of problem characteristics that dictate the relationships between multiple outcomes or relate to generating solutions that may not be evident from the problem representation.

Problem complexity is also partly correspondent with problem difficulty (Campbell, 1988; Lee, 2004). As problem complexity increases, so too does the difficulty associated with processing the components of the problem, as accommodating multiple factors during problem structuring and solution generation places an increasing burden on the working memory of the problem solver (Jonassen, 2000). Conversely, as problem difficulty increases, so too does the complexity associated with identifying the relationships amongst the elements of the problem (Lee, 2004). However, problem difficulty may be determined for reasons that are independent of the characteristics of the problem itself (Campbell, 1988). As Quesada, Kintsch, and Gomez argue (2005), problem complexity does not equal perceived difficulty. They cite studies by Kotovsky, Hayes, and Simon (1985), and Kotovsky and Simon (1990) that demonstrate that changing the problem statement using exactly the same problem structure leads to very different perceptions of problem difficulty. This highlights the influence that problem representation has on both the perceived complexity and perceived difficulty of the problem.

Domain Specificity

The domain from which a problem is drawn from is another characteristic that is influential in determining problem-solving performance (Smith, 1988). Problem-solving activity is sometimes so situational, technical, and specific that it can be difficult for a problem solver with limited knowledge of the domain to solve the problem (Lee, 2004). Therefore, problems may be characterised according to the need for domain specific knowledge along a continuum from decontextualised, abstract problems, to contextualised, situated problems (Jonassen, 1997). In the case of decontextualised problems, the range of information and procedures to solve the problem may be described explicitly (Lee, 2004). Though the possible methods to solve the problem are implicitly hidden in the problem, it is easier to search and find necessary information for solving this type of problem rather than in the contextualised problem (Lee, 2004). Conversely, contextualised problems place an emphasis on situatedness and refer to a context of action, which arises not in the abstract, but in practical and meaningful situations

(Lee, 2004). The differences between decontextualised problems and contextualised problems (Lee, 2004) are summarised in Table 2.5.

Table 2.5. Differences between decontextualised and contextualised situation problems

Characteristic	Decontextualised problem	Contextualised problem
Existence of story context	Has no story to explain where and why the problem eventuated	Has a story to explain where and why the problem eventuated
Domain specific emergence of problem	Does not focus on a specific knowledge domain	Emerges from a specific domain
Time dependency of decision making	Decisions may not be made at the correct moment in relation to the outside environment	Problem solvers should respond to the problem immediately because a decision should be made at the correct moment in conjunction with the consideration of the needs of the external environment
Relation of elements to situation	All elements of the problem are not situated, they are abstract and isolated	All elements of the problem are highly interrelated and interact with each other to achieve the goal
General acceptability of solutions	Paths to acquire solutions and obstacles impeding the solution are clear so that solutions may be accepted by the problem solver	Solutions remain fuzzy. There is no absolute correct answer, nor paths to approach the goal state.
Motivation to solve	A clear path to the solution can motivate the problem solver.	Motivates the problem solver to perceive the problem as urgent, important, and an exciting activity.

Problems of a contextualised or situated nature tend to be ill-structured, which reflects their reliance on domain-specific problem-solving strategies as well as their consistency with the nature of problems encountered in everyday life (Jonassen, 2000). Likewise, problems of a decontextualised nature tend to be well-structured, reflecting their reliance on more domain-general problem-solving skills and procedures (Jonassen, 2000). This illustrates the situated and embedded nature of problem-solving activities, which are contingent on the problem domain and the cognitive operations that are specific to it (Jonassen, 2000; Smith, 1988). The domain specificity, or situatedness, of a problem can thus be denoted as the meaningfulness of the characteristics of a problem as interpreted through a problem solver's prior knowledge and experience during a problem encounter (Lee, 2004).

Problem Representation

Problems can also vary how they are represented to, and thus perceived by, the problem solver (Jonassen, 2000), which is a known factor in determining problem-solving performance (Lee, 2004; Smith, 1988). The delineation of a problem can be considered a set of internal and external representations, whereby the attributes of the external problem representation are perceived, interpreted, and mapped onto the problem solver's internal representation (Jonassen, 2000; Zhang, 1991). Problems in everyday and professional contexts require the problem solver to disambiguate important from irrelevant information and construct a problem space accordingly (Jonassen, 2000; Smith, 1988). The manner in which problem solvers isolate the features of a problem that they perceive as relevant very much depends on how the problem is presented, as even minor differences in presentation can lead problem solvers to construct very different internal representations (Dunbar, 1998).

Zhang (1991) conducted a number of experiments which examined internal and external representations of problems as well as the effect of structural change and its relationship with the nature of problem representation. In the first experiment, the effects of the distribution of internal representations and external representations on problem-solving behaviour were examined. In subsequent experiments, Zhang focussed on the effects of the structural change of a problem on problem-solving behaviour and how the effects were dependent on the nature of the representation. The results of all three studies demonstrated that distributed cognitive activities were produced by the interaction amongst the internal and external representations, where external representations were an indispensable part of the cognitive process of solving problems (Zhang, 1991).

Moreno, Ozogul, and Reisslein (2011) conducted a series of experiments that compared the effects of using concrete or abstract visual problem representations during problem-solving. Three groups of novice students were presented with an instructional program for learning about electrical circuit analysis that included worked-out and practice problems represented with abstract, concrete, or abstract and concrete diagrams and cover stories. Findings demonstrated that the group of students who were presented with abstract and concrete representations were superior during problem-solving practice, suggesting that their advantage relied on the combined cognitive support of both representations.

In a study investigating problem-solving strategies across different presentation modes, Ormrod

(1979) found that different forms of problem presentation led to differences in memory demands, input and processing interference, as well as mathemagenic behaviours, and thus different problem-solving strategies. Ormrod argued that the form in which a problem is presented to a problem solver can determine what information the problem solver stores and the manner in which they store this information. Problem-solving performance was influenced by the use of sequential or simultaneous methods of presentation, and the sensory modalities that were employed (Ormrod, 1979).

Jonassen (2005) citing Kleinmutz and Schkade (1993), provides a similar characterisation of problem representations according to the form of the information items, the organisation of items into structures, and the sequence of items or groups. These characteristics of external problem representation determine the manner in which problems are organised and displayed to problem solvers with the goal of enhancing mental depiction and engaging appropriate problem-solving processes (Jonassen, 2005; Zhang, 1991). An important factor for training based on problem-based learning thus entails deciding how to present the problem to the problem solver, as external representations are more than merely inputs to an internal representation process during problem-solving (Jonassen, 2005). The designer assumes responsibility for constructing the problem space for the problem solver, and in doing so, provides or withholds contextual cues, prompts, or other clues about information that needs to be included in the problem solver's problem space (Jonassen, 2000). The fidelity of the representation also needs to be considered, as a problem may be delineated in a manner that is faithful to its natural complexity and modality, or instead as a filtered simulation (Jonassen, 2000). Problems with higher fidelity may be more likely to transfer to the real world and may also be more motivational for the problem solver (Norman, 1988). Such problems carry more contextual information which inevitably aids the subsequent recall of information, however, the extent to which these features are unrelated, or spuriously related to the problem at hand, can be a handicap rather than an asset to learning (Norman, 1988). Consequently, the notion of fidelity in problem representation is especially pertinent in solving problems that are situated within a real world context, as invariably some of the detail will be lost in providing a practical problem representation to the problem solver.

External Factors - Summarised

Problems can vary according to their structuredness, complexity, and domain specificity, all of which have been identified as factors which affect problem-solving performance. These factors also have a perceived value which is determined in accordance with the problem-solver's

knowledge of the problem domain. Additionally, the representation of the problem can vary according to its form, organisation, and sequencing, all of which influence the development of the problem space and the problem-solving processes that are employed. The external factors affecting problem-solving performance identified in the literature review are summarised in Table 2.6 together with relevant criteria for the purposes of evaluation:

Table 2.6. Factors external to the problem-solver which affect problem-solving performance.

Factor	Criteria for evaluation
Structuredness	· Extent of existing domain specific knowledge and general problem-solving skills · Perceived familiarity of the problem
Complexity	· Perceived uncertainty of the problem-solving context · Perception of related entities within the problem domain · Recognition of problem complexity
Domain specificity	· Perceived meaningfulness of the problem · Problem-solving strategies employed · Extent to which problem is contextualised
Problem representation	· Perception of the problem representation · Identification of relevant problem features · Identification of relationships · Problem-solving strategies employed

2.1.4 The Nature and Function of Problem-based Learning

Having examined the nature of problems, the process of problem-solving and the factors that influence this process, a more informed examination of problem-based learning can now be conducted.

Problem-based approaches to learning have a long history of advocating experience-based education. Psychological research and theory suggests that students can learn both content and thinking strategies through the experience of solving problems (Hmelo-Silver, 2004). This process is characterised by the movement of learners towards the acquisition of knowledge and skills through a staged sequence of problems presented in context, together with associated learning materials and support from teachers or facilitators (Boud & Feletti, 1997). A wide variety of educational methods which can address quite different educational objectives are referred to as problem-based learning, however the common denominator among them is the use of problems in an instructional sequence (Barrows, 1986). Although there is no universally agreed set of practices in problem-based approaches to define them as such, the following features can be considered as characteristic of problem-based learning (Boud & Feletti, 1997;

Hmelo-Silver, 2004; Kolmos et al., 2007; Ma, O'Toole, & Keppell, 2007):

- Student learning centres on a complex problem which is often drawn from the real world or presented as a simulation of professional practice or a 'real life' situation;
- Students' critical thinking is guided via the provision of limited resources to help them learn from defining and attempting to resolve the given problem;
- Learning is student-centred, whereby students engage in self-directed learning where they identify their own learning needs and appropriate use of available resources. Learners assess and reflect on what they have learned and the strategies they have employed, and;
- A teacher or facilitator acts to expedite the learning process, rather than to provide knowledge.

2.1.4.1 Goals of Problem-based Learning

Problem-based learning can be used in a wide variety of scenarios to fulfil many different educational objectives (Barrows, 1986), but its primary focus remains the accumulation of knowledge that arises from the process of solving problems (Boud & Feletti, 1997; Norman, 1988). The focus of learning in this context is on the activation of prior knowledge and subsequent acquisition of new knowledge in order to address a given problem, rather than merely the application of prior knowledge to this end (Hughes Caplow, Donaldson, Kardash, & Hosokawa, 1997; Norman & Schmidt, 1992). Broadly speaking, the instructional goals of problem-based learning consist of both knowledge-based and process based objectives (Barrows, 1986; Hmelo-Silver, 2004; Norman, 1988; Norman & Schmidt, 1992; Savery, 2006):

- Construction of an extensive and flexible knowledge base for use in context;
- Development of effective problem-solving and reasoning skills;
- Mastery of general principles or concepts that can be transferred to solve similar problems, and;
- Acquisition of prior examples that can be used in future problem-solving situations of a similar nature;

Contextual Knowledge

Constructing an extensive and flexible knowledge base involves the integration of information

across multiple domains (Hmelo-Silver, 2004). Such knowledge is organised coherently around the underlying principles of the problem domain (Hmelo-Silver, 2004), and is flexibly conditionalised to the extent that it can be fluently retrieved and applied under varying and appropriate circumstances (Hmelo-Silver, 2004). Learning new knowledge within a problem-solving context can foster retrievability and use when needed for the solution of similar problems because education is most effective when it is undertaken in the context of future tasks (Barrows, 1986; Norman & Schmidt, 1992). In order to encourage learners to develop flexible knowledge and effective problem-solving skills, learning must be embedded in contexts that require the use of these skills (Hmelo-Silver, 2004). Learning that is driven by the challenge of practice and integrated into reasoning that evaluates and resolves problems, promotes the structuring of knowledge to support practice (Barrows, 1986).

Problem-solving Skills

Problem-solving and reasoning skills must be shaped and perfected through repeated practice and feedback in order to be effective and efficient (Barrows, 1986). Through continuous exposure to problems that are situated within a real life context, learners can develop their ability to evaluate and identify the important aspects of problems as well as their decision making processes regarding appropriate actions and strategies to pursue (Barrows & Tamblyn, 1980). These skills include hypotheses generation, inquiry, data analysis, problem synthesis and decision making proficiencies (Barrows, 1986), as well as problem analysis, which plays a key role in problem-based learning (de Grave, Boshuizen, & Schmidt, 1996). Developing effective problem-solving skills also cultivates the ability to apply appropriate metacognitive and reasoning strategies (Hmelo-Silver, 2004).

Knowledge Transfer Between Similar Problems

Knowledge transfer between similar problems is contingent on the extent to which a concept or principle learned in one context can be transferred or applied to a problem which, while different in initial appearance, requires the same principles for resolution (Norman, 1988). There are two different mechanisms by which transfer of specific skill and knowledge takes place; *low road* transfer and *high road* transfer (Salomon & Perkins, 1989). The low road to transfer depends on extensive and varied practice of a skill to near automaticity:

> A skill so practised in a large variety of instances becomes applied to

perceptually similar situations by way of response or stimulus generalisation...
Unfortunately, learning in many natural settings and in many laboratory
experiments does not meet the conditions for low road transfer: much practice,
in a large variety situations, leading to a high level of mastery and near-
automaticity (Salomon & Perkins, 1989, p. 22).

In contrast, high road transfer occurs by intentional mindful abstraction of something from one
context and application in a new context (Salomon & Perkins, 1989). Such transfer can either be
of the forward-reaching kind, whereby one mindfully abstracts basic elements in anticipation for
later application, or of the backward-reaching kind, where one faces a new situation and
deliberately searches for relevant knowledge already acquired (Salomon & Perkins, 1989).

Problem-based learning demands *mindfulness* from learners and provides a context where
mentally demanding activities occur (Pedersen & Liu, 2003). Mindfulness refers to the
volitional, metacognitively guided employment of non-automatic mental processes, and is a
necessary ingredient for high road transfer (Salomon & Perkins, 1989). Thus, learners are more
likely to be able to transfer their learning if it has taken place within a context that requires
mindfulness (Pedersen & Liu, 2003). However, transfer occurs only under specific conditions
which often are not met in everyday life (Salomon & Perkins, 1989). In these scenarios, the high
road mechanism does not operate because there is nothing to provoke the active
decontextualisation of knowledge (Salomon & Perkins, 1989). Thus, in order to provide high
road transfer under problem-based learning, certain conditions must be met in order to elicit the
mindful, deliberate processes that decontextualise the cognitive elements that are candidates for
transfer (Salomon & Perkins, 1989). To this end, Norman and Schmidt (1992, p. 150) provide
two prerequisites for successful transfer from a learning session around a problem:

1) The problem must be approached in a problem-solving modality without much
   foreknowledge of the domain of the solution or the underlying problem, and;
2) The problem solver must receive corrective feedback about the solution immediately
   upon completion.

The first prerequisite indicates the importance of the external problem representation in
facilitating effective learning transfer. The provision of any information that detracts from the
problem-solving process, such as the common expedient of identifying a problem in advance as
fitting a particular classification or typology, may result in a serious decrement in transfer

(Norman & Schmidt, 1992). By employing an external representation that does not identify the nature of the underlying concept of the problem, learners are forced to reason and reflect during problem solution (Norman & Schmidt, 1992), thus engaging the processes required for mindfulness and high road transfer. It is the internal representation of a problem that determines transfer, and this representation can operate independently of the stimulus features of problems (Kotovsky & Fallside, 1989). Problems should therefore be designed to facilitate the development of internal representations which produce positive transfer in order for them to be useful in subsequent problem-solving experiences (Kotovsky & Fallside, 1989).

In order to promote transfer between problem-solving experiences, learners must also receive corrective feedback during the course of attempting to solve a problem (Norman & Schmidt, 1992). The provision of feedback has been shown to be an effective scaffolding mechanism during the problem-solving process which supports the learner's search for a solution (Jonassen, 1997; Tudge, Winterhoff, & Hogan, 1996; Zumbach & Reimann, 2003). By enhancing how learners participate within a problem-based learning environment, it may be possible to affect their work on similar tasks in different domains, as a learner who is attuned to the constraints and affordances of a given situation should also be better able to recognise similar features in other situations (Pedersen & Liu, 2003). This suggests that improving problem-solving performance via the provision of feedback should also enhance the transfer of key components and principles between similar problems.

A series of experiments by Needham and Begg (1991), for example, compared the effects of problem-oriented processing against memory-oriented processing on spontaneous analogical transfer, which relates to the use of information from one problem to another without an explicit hint to do so. The subjects in these experiments were presented with a series of training problems to either solve or remember, after which the underlying principles of the problems were explained to them using a blackboard to facilitate understanding. The results from the first experiment showed that the problem-oriented subjects were able to transfer the concept to a new problem 90% of the time, compared to approximately 60% for memory-oriented subjects. Subsequent experiments demonstrated the role that feedback played in this process. When no feedback was provided, the problem-oriented subjects faired little better than their memory-oriented counterparts. Furthermore, feedback about the problem solution did not offer any advantage to the memory-oriented subjects, whose performance consistently remained at approximately 60% for all experiments. This indicates that merely engaging in problem-solving activity is not sufficient for spontaneous analogical transfer; feedback in the form of an

explanation is also required.

Prior Examples

The easiest, most efficient and least error prone way to solve a problem lies in recalling a solution on the basis of similarity with a previously solved problem (Norman & Schmidt, 1992). In this manner, learning from worked examples can help learners form appropriate representations of concepts and situations within the problem domain (Jonassen, 1997). Research in cognitive science provides extensive evidence for a natural progression in cognitive skill centring on worked examples as learning aids, and begins with learners studying examples prior to problem-solving (Conati, Muldner, & Carenini, 2006). As instructional devices, worked examples typically include a problem statement and a procedure for solving the problem which together are intended to demonstrate how other similar problems might be solved (Atkinson, Derry, Renkl, & Wortham, 2000). At first glance, it may seem that the application of worked examples may be more consistent with low road transfer, as they depict a particular procedure under narrowly defined conditions, and as such cannot be applied to other problems with differing solutions. However, worked examples can foster adaptive, flexible transfer amongst learners if a wide range of worked examples illustrating multiple strategies and approaches to similar problems are provided (Conati et al., 2006). These examples need to be practised extensively in order to facilitate the acquisition of problem schemas and the transfer of those schemas to novel problems (Jonassen, 1997). Numerous examples should be provided, as they serve to clarify abstract principles and add information to the abstract schema that result from learners' generalisations of the problems with which they have gained experience (Eva, Neville, & Norman, 1998).

2.1.4.2 Benefits of Problem-based Learning

Educators are attracted to problem-based learning approaches due to their emphasis on active, transferable learning, motivational potential, and compatibility with modern theories of adult learning (Finucane, Johnson, & Prideaux, 1998; Hmelo-Silver, 2004). The advantages of problem-based learning detailed in relevant literature can be summarised as follows (Barrows & Tamblyn, 1980; Bentley, 2004; Finucane et al., 1998; Norman, 1988; D. F. Wood, 2003):

- Participants in problem-based learning prefer their experience over more traditional classroom approaches. problem-based learning is realistic, stimulating, and highly

motivating for participants;

- Problem-based learning fosters deep learning, where learners interact with learning materials, relate concepts to everyday activities, and improve their understanding, rather than fast learning;

- Problem-based learning is consistent with constructivist approaches whereby learners activate prior knowledge and build on existing conceptual knowledge frameworks;

- Information, concepts, and skills learned during problem-based learning are put into memory in association with a problem. This allows the information to be recalled more easily when another problem is faced in which the information is relevant, as knowledge is much better remembered or recalled in the context in which it was originally learned. Furthermore, recall is constantly reinforced and elaborated by subsequent work with other problems;

- Problem-based learning fosters active learning, improved understanding, and retention and development of lifelong learning skills. Self-directed learning skills are enhanced and retained;

- The learner is able to use the problem as a focus for study of many different subjects, actively integrating this information into a system that can be applied to the problem at hand and to subsequent and future problems, and;

- Problem-based learning allows learners to develop generic skills and attitudes that are desirable in their future practice. This includes the development of essential problem-solving skills and critical thinking and reasoning abilities.

Problem-based learning is not without its potential shortcomings, however. The success of problem-based/student-centred learning depends on students disciplining themselves to work with an unknown and possibly puzzling problem in a way that will challenge the development of their problem-solving skills and stimulate relevant self-directed learning (Barrows & Tamblyn, 1980, p. 13). Furthermore, problem-based learning can be stressful for both learners and teachers alike (Finucane et al., 1998; MacKinnon, 1999), and can also overload the learner in regard to how much self-directed learning is required and which information is relevant and useful to the problem scenario at hand (D. F. Wood, 2003). Problem-based learning approaches requires considerable attention to learning objectives, identification of appropriate educational issues, and knowledge of relevant cognitive processes and how they should be learned and evaluated (Barrows & Tamblyn, 1980). This highlights the significance of identifying the important aspects of problem-based learning so that effective learning environments can be designed and developed.

2.1.4.3 The Problem-based Learning Process

Problem-based learning is focused and experiential learning, that is organised around the investigation and resolution of problems that often exist within a real world context (Torp & Sage, 2002). This process can be mildly or highly structured and begins with the presentation of a problem scenario to the learner (Barrows & Tamblyn, 1980; Boud & Feletti, 1997). Learners formulate and analyse the problem by identifying the relevant cues and facts which helps them to represent and define the problem in a clear and concise manner, summarising key information (Hmelo-Silver, 2004; Johnson, Finucane, & Prideaux, 1999). As learners improve their understanding of the problem, they generate hypotheses about possible solutions and the underlying aspects of the problem scenario (Hmelo-Silver, 2004; Johnson et al., 1999). Based on this exercise, learners identify what they know and what they do not know relative to the problem scenario, which is an important part of the problem-based learning process (de Grave et al., 1996; Hmelo-Silver, 2004). These knowledge deficiencies form the basis of the learning issues that students research during their self-directed learning which is subsequently used to re-evaluate the hypotheses in light of what has been learned (de Grave et al., 1996; Hmelo-Silver, 2004; Johnson et al., 1999). At the completion of the problem, learners reflect on the abstract knowledge that has been gained (Hmelo-Silver, 2004; Johnson et al., 1999). The problem-based learning process can be summarised diagrammatically in Figure 2.3, as follows:

Figure 2.3. The problem-based learning cycle (Hmelo-Silver, 2004, p. 237)

2.1.4.4 Design Considerations in Problem-based Learning Environments

Problem-based learning scenarios should encourage learner interaction with the problem in a way that challenges and develops their reasoning skills and stimulates their self-directed study (Barrows & Tamblyn, 1980). These scenarios should also facilitate the learner's ability to evaluate their skills and knowledge in working with the problem (Barrows & Tamblyn, 1980; Hmelo-Silver, 2004). Broadly speaking, the design variables to be considered to this end can be separated into how the problems are designed and formatted, or task considerations, and the manner in which the learning process is directed and controlled, or control considerations (Arts, Gijselaers, & Segers, 2002; Barrows, 1986).

Task Considerations

Problem-based learning begins with the presentation of a problem to the learner, which represents the entry point for the learner into the learning process. The design and format of the

problems used in problem-based learning are thus a major variable in determining effectiveness (Barrows, 1986; R Oliver & Omari, 1999). The degree of structuredness of the problem is key in this regard, as this represents the number of unknown or uncertain elements in the problem equation. The structuredness of a problem can thus be characterised as complete case, partial problem simulation, or full problem simulation, as summarised in Table 2.7 (Barrows, 1986):

Table 2.7. Structuredness of problems as design variables in problem-based learning

Structuredness	Description
Complete case	Learners are provided with an organised summary of the facts that they need to know about the problem. The learners' challenge is to decide what may be causing the problem and what can be done to resolve it on the basis of the evidence provided.
Partial problem simulation	Learners are provided with a number of the facts about the problem and must decide on a limited number of inquiry actions or decisions, or to choose actions and decisions from the alternatives presented.
Full problem simulation (free enquiry)	Learners are given the initial presentation of the problem and have to assemble the important facts through free enquiry, as occurs in the real world, using reasoning.

The structuredness of the problem should be determined in consultation with the learner's level of understanding of the subject domain (D. F. Wood, 2003). Problems that are too ill-structured and provide limited information can impede the ability of learners to work in a meaningful manner with that information if their knowledge of the problem domain is inadequate (Arts et al., 2002). Good problems should be open-ended enough to support conjecture, flexible thinking, and creative problem-solving, but not too ill-structured to cause learners to digress too far from the intended learning outcome or diminish intrinsic motivation (Hmelo-Silver, 2004; R Oliver & Omari, 1999). Problem selection should also be carried out in accordance with the learning objectives of the problem-based learning exercise. These objectives should be defined in advance and presented in a manner that prompts or increases the likelihood of them being identified and defined by the learner after studying the problem scenario (Johnson et al., 1999; D. F. Wood, 2003).

The format of the problem dictates its organisation and arrangement in accordance with the overall learning objectives and the nature of the information to be acquired (Charlin, Mann, & Hansen, 1998). It encompasses the way in which the problem is presented, its complexity, and the number of sessions that the problem may be spread over, including whether the problem is intended to be studied once or revisited a number of times at different levels (Charlin et al.,

1998; Cheong, 2008; Hmelo-Silver, 2004). Charlin, Mann and Hansen (1998) suggest that the number of sessions employed should be a product of the predefined learning objectives with a choice between fewer, more complex problem scenarios, or shorter, less complex scenarios that are greater in number. Shorter, but more numerous cases may be used in order to provide a greater number of examples, with the aim of enhancing problem-solving when new problems are encountered (Charlin et al., 1998). This suggests that the use of shorter, but more frequent problem scenarios may be better suited to fostering the transfer and application of knowledge between different problem scenarios.

The type of information presented in the problem also has important implications regarding the transfer and application of knowledge in future situations. As Brown, Collins and Duguid (1989) have argued in their work on situated cognition, knowledge is situated within the activity, context, and culture in which it is developed and used. Thus, presenting the problem to the learner in a manner that is consistent with a real world problem scenario will serve the transfer and application of knowledge accumulated between them. To facilitate this, the problem should be presented with the type of information normally available within the context of the real world scenario, and not as a pre-digested summary containing information that would usually result only from further inquiry (Barrows & Tamblyn, 1980). A problem-based on a real world medical scenario, for example, would be expected to present the problem solver with information which details a patient's condition, symptoms, and other information such as heart rate or body temperature. This type of authentic learning is consistent with the concept of encoding specificity, which suggests that the closer the resemblance between the situation in which something is learned and the situation in which it is applied, the better the performance (H. G. Schmidt, 1983, p. 12).

The concept of authentic learning also applies to the medium which is used for the external problem representation (Keppell, 2008). Many problem-based learning scenarios rely primarily or exclusively on written or oral problem statements and learning resource material, which may adversely effect transfer between those problems depicted and similar ones in real life (Hoffman & Ritchie, 1997). Multimedia learning environments are an alternative to these more traditional methods of presenting problems, promoting constructivist learning which enables problem-solving transfer (Mayer, 1999). When appropriate technologies can be selected as required and used as cognitive tools to solve complex problems, the responsibility for learning shifts to the learner rather than the designer of the virtual learning environment (T. C. Reeves & Oliver, 2007). Providing video, sound, and still-images associated with events instead of relying solely

on text, offers the potential to enhance the fidelity of problem scenarios associated with those events (Hoffman & Ritchie, 1997, p. 112). By providing richer contexts, individualising practice, feedback, and reflection; and facilitating more authentic assessment, multimedia exhibits the potential to strengthen conventional problem-based learning (Hoffman & Ritchie, 1997).

Thus, problem design should facilitate practice and evaluation of the important stages of the problem-solving process, including data perception and interpretation, problem formulation, hypotheses generation, inquiry strategy, decision making, and sequential management (Barrows & Tamblyn, 1980). The problem format should allow for sequential, interdependent actions to be taken in the evaluation and resolution of the problem, whilst also accounting for varying approaches, and their subsequent outcomes, that result from the different skills, strategies, or styles of the learner (Barrows & Tamblyn, 1980). The design and format of the problem should also generate sufficient intrinsic interest for learners relevant to future practice and contain cues to encourage learners to seek explanations for the issues presented (D. F. Wood, 2003). Authentic problem descriptions should also be employed to foster higher order reasoning skills that are relevant for practice (Arts et al., 2002; T. C. Reeves, Herrington, & Oliver, 2002).

Task Considerations - Summarised

The design and format of the problem scenarios utilised in problem-based learning are factors which influence the learning process. These factors determine the nature of the information that is contained within the problem statement and also the manner in which it is presented to the learner. The task considerations for problem-based learning scenarios identified in the literature review are summarised in Table 2.8 along with corresponding criteria for evaluation:

Table 2.8. Task considerations for problem-based learning

Factor	Criteria for evaluation
Problem design	
Authenticity of information	• Consistency of information
Problem format	
Problem representation (as per Table 6)	• Perception of the problem representation • Identification of relevant problem features • Identification of relationships • Problem-solving strategies employed

Control Considerations

The manner in which learning is directed and controlled within problem-based learning environments is another key design element warranting consideration. The learning process can be tutor directed, partially learner and tutor directed, or learner directed, with responsibility for determining the amount and sequence of information to be learned delegated accordingly (Barrows, 1986). In scenarios where the learning is partially learner and tutor directed, the tutor performs a guidance role using facilitatory teaching skills in place of direct intervention (Johnson et al., 1999), which can be described as follows:

> Generally, the role of the tutor in PBL is characterised by interaction that is facilitative rather than directive, and in which information giving by the tutor is subordinate to assisting students in the process of activating, identifying, accessing, analysing and applying information, and of developing reasoning processes and knowledge structures (Charlin et al., 1998, p. 328).

In problem-based learning, the facilitator is an expert learner, able to model effective strategies for thinking and learning, rather than an expert in the content itself (Hmelo-Silver, 2004). The facilitator's role is to shepherd learners through the stages of the problem-based learning process, modeling these stages for learners and prompting their self-directed learning (Charlin et al., 1998; Johnson et al., 1999). Facilitation in problem-based learning environments thus emphasises guiding the learner over the provision of direct instruction:

> The student does not listen, observe, write, and memorise; instead, he is asked to perform, think, get involved, commit himself, and learn by trial and error. He is asked to learn both cognitive reasoning skills and the psychomotor skills of interview and examination, and to identify learning needs made apparent by his work with a problem. In this setting, the teacher's role can be seen as that of a guide or facilitator (Barrows & Tamblyn, 1980, p. 83).

The amount of external support required from the facilitator depends on the learner's prior learning and their understanding of the problem-based learning process (Davis, 1973). As learners become more experienced, the support provided by the facilitator fades where the learner is afforded greater ability to direct their learning (Arts et al., 2002; Hmelo-Silver, 2004). Providing the learner with a degree of control is an essential aspect of effective learning

environments allowing the learner to be active, autonomous, and highly intrinsically motivated (Arts et al., 2002). Learners must be afforded ownership of the learning process in order for the problem-solving task to be authentic and serve as a stimulus for problem-solving and self-directed learning (Savery & Duffy, 2001).

The facilitator is responsible both for moving learners through various stages of problem-based learning and for monitoring their progress by asking leading questions, challenging thinking, and raising issues or points that need to be considered (Barrows & Tamblyn, 1980; Hmelo-Silver, 2004). The problem-based learning facilitator attempts to help learners 'help themselves' in the educational process by (Barrows & Tamblyn, 1980; Hmelo-Silver, 2004):

- Guiding the development of higher order thinking by encouraging learners to justify their thinking and;
- Externalising self-reflection by directing appropriate questions to individuals.

The most critical activity that the facilitator performs within a problem-based learning environment is in the questions that they ask the learner as part of their consulting and coaching activity (Savery & Duffy, 2001). It is essential that facilitators value the learner's thinking as well as challenge it by inquiring at the boundaries of the learners understanding and not merely telling the learner what to do or how to think (Savery & Duffy, 2001). Facilitation is thus a subtle skill which involves knowing when an appropriate question is called for, when learners are going off-track, and when the problem-based learning process is stalled (Hmelo-Silver, 2004). A competent facilitator can guide learners indirectly while they are actively working on a problem, stopping them at crucial points to ask about their thinking, their concept of the problem, their hypotheses and how their actions relate to these, and how they intend to rank, refine, or eliminate hypotheses (Barrows & Tamblyn, 1980).

The provision of information, which is used by learners to augment their study and to address the learning needs raised by the problem, is also affected by the degree to which the learner is considered responsible for their own learning (Charlin et al., 1998). Key sources of information may be identified for learners as part of the problem design, or learners may be responsible for identifying their own resources in the interest of providing the most freedom for different learning approaches and the most encouraging environment for the development of self-directed learning skills (Charlin et al., 1998). Learners should be encouraged to discover the proper use of these information sources as part of the problem-based learning process (Davis, 1973) as

good problem scenarios often require multidisciplinary solutions where learners seek information from a variety of resources (Hmelo-Silver, 2004; Savery, 2006; D. F. Wood, 2003). The necessity of gathering information from a wide range of sources allows learners to see knowledge as a useful tool for solving problems and geting them involved in the problem-solving process (Hmelo-Silver, 2004; D. F. Wood, 2003).

Other control considerations that warrant deliberation include the role of reflection, the provision of feedback, and the use of assessment within problem-based learning environments. To appropriately solve a problem in a problem-based learning environment, it is important that learners reflect on their understanding of an issue, acquire new knowledge to help in developing a solution, and think about how their new knowledge can be used to address the problem situation (Song, Grabowski, Koszalka, & Harkness, 2006). Reflecting on the relationship between problem-solving and learning is thus a critical component of problem-based learning and is needed to support the construction of extensive and flexible knowledge (Hmelo-Silver, 2004, citing Salomon & Perkins, 1989). Reflection on the possible causes of a problem may lead to practical actions, such as separating the problem into more manageable components, or abstract actions, such as developing deeper understandings of the problem, issues, and concepts associated with what is being reflected upon (Wulff, Hanor, & Bulik, 2000). The potential for high road transfer inherent in problem-based learning environments can also be increased as a result of learner reflection (Salomon & Perkins, 1989).

Reflection is incorporated throughout the problem-based learning process to help learners relate their new knowledge to their understanding, mindfully abstract their knowledge, and understand how their learning and problem-solving strategies might be reapplied (Hmelo-Silver, 2004). For learners, reflection can also support and prompt initiative and responsibility, leading to engagement and empowerment (Wulff et al., 2000). In order for this to occur, opportunities and support for reflection on both the content that is learned and the learning process itself must be catered for within the learning environment (Savery & Duffy, 2001). This should be provided by the facilitator, modelling reflective thinking throughout the learning process and supporting the learners in reflecting on their strategies for learning as well as what they learned (Grunefeld & Silen, 2000; Hmelo-Silver, 2004; Savery & Duffy, 2001).

Other design elements, such as teaching methods, learning environment features, and scaffolding tools, can also be used to prompt reflective thinking (Song et al., 2006). Teaching methods, such as inquiry-oriented and explanation-oriented instruction, prompt reflective thinking by asking reflective questions and guiding learners to reflect directly on important

problem related concepts (Song et al., 2006, citing Moon, 1999; Virtanen, Kosunen, Holmberg-Marttila, & Virjo, 1999). Design elements serve to make the learning environment active and student-centred, which allows learners to think before answering. Learner-controlled instruction, as well as cooperative and collaborative learning, are also important as flexible, active, and student-centred problem-based learning environments prompt reflective thinking (Song et al., 2006, citing Rowe, 1974; Williams, 1996; Aldred & Aldred, 1998). Scaffolding tools such as structured journals and diaries, question prompts, and concept-mapping activities can also be used to prompt reflective thinking during problem-based learning (Hmelo-Silver, 2004; Song et al., 2006, citing Barrow, 1998; Griffith & Frieden, 2000; Kinchin & Hay, 2000).

Solving a problem in a problem-based learning environment similarly requires the learner to utilise feedback via their interaction with the facilitator and task environment to guide their search for a solution (Arts et al., 2002; Newell & Simon, 1972; Norman & Schmidt, 1992; Savery, 2006). The provision of feedback is an important design consideration in problem-based learning environments which can be provided "at the tactical level of each well-structured step, or at the strategic level concerned with higher-order rules and problem space structures" (Foshay & Gibbons, 2005, p. 11). Learners must be provided with immediate information, in a realistic form, regarding the results to their actions in order to guide the problem-based learning process (Barrows & Tamblyn, 1980; Charlin et al., 1998; Norman & Schmidt, 1992). Thus, the type of information provided as feedback and the manner in which it is presented to the learner is important for contextually authentic learning.

Learner assessment in problem-based learning is governed by principles similar to those applied to the assessment of learners more generally and should be designed to test the learner's ability to fulfil predefined learning objectives and assist them in developing knowledge that is deemed pertinent (Davis, 1973; Norman, 1997). The goals of problem-based learning are both knowledge-based and process-based, where learners need to be assessed on both dimensions at regular intervals to ensure that they are benefiting as intended from the learning approach (Savery, 2006). If achievement of an important part of a learning process is not assessed, that aspect of the process is at risk of neglect by the learner (Charlin et al., 1998). This is particularly relevant for problem-based learning modelled on real world scenarios, where the fulfilment of learning objectives may be highly important. Consider, for example, a medical student engaged in a problem-based learning exercise which required them to correctly diagnose a patient's illness based on a specific set of symptoms. Without assessment, there would be no know way of determining whether the student would be competent enough to correctly diagnose patients in

a real world scenario. Learners thus need to be able to recognise and articulate what they know and what they have learned (Savery, 2006).

The degree of control that the learner has over the learning process, whether tutor directed, partially learner and tutor directed, or learner directed, is key in determining which assessment methods may be appropriate (Barrows, 1986; Swanson, Case, & van der Vleuten, 1997). As detailed in Figure 2.4, the tutor and learner directed approaches to problem-based learning can be viewed as opposite ends of a continuum representing the learner's degree of control over the learning process (Swanson et al., 1997). The space between them consists of various permutations of learning that are partially learner and tutor directed.

Tutor-directed   Partially tutor and learner directed   Learner-directed
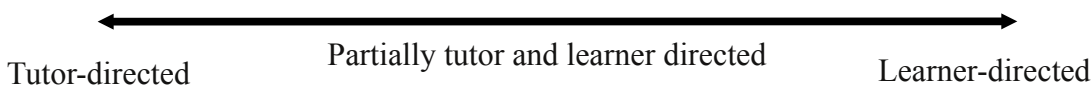
Figure 2.4. The learning process control continuum

Learner-directed or 'open discovery' approaches are those in which learners have the responsibility for determining what to learn, when to learn, and how to learn (Barrows, 1986; Swanson et al., 1997). Assessment in these approaches often focus on one or more process variables such as self-directedness, motivation, effort, problem-solving, and attitudes (Swanson et al., 1997). Assessing learning outcomes in the open discovery approach is generally viewed as problematic, because each learner is encouraged to pursue the problem-solving process differently (Swanson et al., 1997).

Conversely, tutor-directed or 'guided discovery' methods utilise specific learning objectives which are identified in advance to organise the learning process (Barrows, 1986; Swanson et al., 1997). These may be highly structured, with careful sequencing of instructional experiences, and learners may or may not be aware of the structure and specific learning objectives that have been devised for them (Swanson et al., 1997). Assessment of learning outcomes poses fewer problems for problem-based learning utilising guided discovery approaches because the same learning objectives that guide problem development may also be used to guide test development (Swanson et al., 1997). As a consequence, assessment in guided discovery approaches may be focussed on both learning processes and learning outcomes (Swanson et al., 1997).

Several assessment methods may be used to measure the learners' use of elaborated knowledge

in solving problems (Swanson et al., 1997). The behaviour of the learner and their approach to learning is influenced by the assessment methods which are used within a problem-based learning environment, so their selection warrants contemplation (D. F. Wood, 2003). There are certain characteristics of all assessment approaches that need to be considered carefully whenever they are employed (Barrows & Tamblyn, 1980):

- *Process versus context* - Content evaluation is concerned with the information, concepts, and principles the learner has acquired in memory and can bring forth by recognition, recall, or associations. Process evaluation, on the other hand, is concerned with the learner's ability to observe data, solve problems or demonstrate problem-solving processes relevant to the problem in question.
- *Process versus outcome* - Outcome evaluation is concerned with measuring the learner's ability to meet the predefined learning outcomes of the problem-based learning exercise.
- *Reliability* - Measures the consistency of the assessment in terms in terms of how free it is from the effects of uncontrolled or confounding variables, and how prone to error the sampling is.
- *Validity* - Refers to the extent to which the assessment provides an accurate, true reflection of the characteristic it is purported to measure.
- *Fidelity* - Describes the extent to which the assessment resembles or mimics the real-life setting in which the characteristic is to be measured.
- *Feasibility* - Refers to the logistical difficulties that the learner may encounter in undertaking the assessment, as well as the ease with which the assessment can be provided.

Learner-directed approaches to problem-based learning might be expected to utilise assessment methods that are more process oriented that context or outcome oriented. A learner's individual approach to solving a problem may not be consistent with the predefined learning objectives or knowledge that are to be acquired as part of the learning process. As the learner is responsible for their own learning in these approaches, it is of more value to identify which processes are employed and how effective they are in solving the problem.

Conversely, tutor-directed approaches to problem-based learning may be expected to be more context and outcome oriented rather than process oriented. Although process oriented evaluation could still be conducted, the value of assessing which processes learners use to solve the

problem and how effective they are is of less significance, as the learner has diminished control over the learning process. Under tutor-directed approaches, it is of more value to determine whether the learner has satisfied the learning objectives and accumulated the desired knowledge during the course of solving the problem.

In this manner, the degree of learner control over the learning process determines the orientation of assessment according to process, or context and outcome based evaluation. The reliability, validity, feasibility, and fidelity of the assessment in turn determine the consistency, accuracy, and authenticity of the measure, as well as how difficult it may be to undertake and implement.

Control Considerations - Summarised

The degree of learner control, the provision of information, reflection, feedback, and assessment were identified in the literature as key aspects in the control of problem-based learning. These factors are summarised with corresponding evaluation criteria in Table 2.9.

Table 2.9. Control considerations for problem-based learning

Factor	Criteria for evaluation
Feedback	· Perception and understanding of feedback · Modification of user behaviour due to feedback · Relevance of feedback · Integration of feedback
Assessment	· Validity of assessment · Fidelity of assessment · Integration of assessment
Information	· Extent of information available · Integration of information · Application of information
Learner control	· Control of the learning process · Integration of learner control · Suitability of learner control
Reflection	· Identification and development of new knowledge · Future applications of new knowledge · Integration of reflection

2.1.4.5 Problem-based learning in Virtual Environments

The combination of computer technology and pedagogical frameworks offer great potential for situating training and education within realistic, authentic, and engaging learning environments

(Donnelly, 2010; Hallinger, 2005; Kirkley & Kirkley, 2004; Savin-Baden, 2009). Computer-generated learning environments can be used within this capacity to enhance understanding, improve performance, and assess competence, whilst providing a means of making experiential learning reproducible and reusable (Alverson et al., 2005; Dalgarno & Lee, 2009; Persky et al., 2009)

Computer technology allows problem-based learning approaches to take on new forms and provide new opportunities for communication and access to information (Dirckinck-Holmfeld, 2009). Hallinger (2005) provides a taxonomy of technology uses in this regard according to the problem presentation, the learning process, scaffolding tools, and the product representation. Computer technology can be used in the presentation of the problem to provide the learner with a more immediate and richer presentation of the problem situation compared to written or verbally conveyed cases (Hallinger, 2005; Hoffman & Ritchie, 1997). Contextual cues, relationships, explicit and implicit goals, underlying processes can be presented in a manner that requires learners to recognise and search for this information without being explicitly told what is relevant (Hallinger, 2005). This is particularly true of 3D virtual environments providing users with unrestricted control of their movement and orientation within a three-dimensional space. A more thorough examination of the characteristics and capabilities of 3D virtual environments, and their compatibility with problem-based learning, is contained in Chapter 2.4.

A significant body of research points to the learning and educational benefits of marrying 3D virtual environments with problem-based learning approaches. Students in a study conducted by Alverson, Saiki Jr, Caudell, Summers, and Panaiotis, et. al. (2005) stated that the opportunities to make mistakes and repeat actions during problem-solving within a 3D virtual environment were extremely helpful in learning specific principles. Similarly, a study by Jensen, Seipel, von Voigt, Raasch, and Olbrich, et. al. (2004) found that participants appreciated three-dimensional representation because it gave them a vivid, interactive view of objects within the environment during problem-solving activities. More recent studies have demonstrated the value of integrating problem-based learning approaches within 3D virtual environments in terms of capturing the attention of students and triggering self-directed learning, creating a sense of empowerment fostered by access to learning resources, and developing an increased willingness to play, explore, and experiment (Vosinakis, Koutsabasis, & Zaharias, 2011; Warren, Dondlinger, McLeod, & Bigenho, 2012).

2.1.5 Summary for Problem-based Learning

Problem-based learning is a pedagogical approach to learning that is situated in problem-solving experience. It emphasises the development of problem-solving skills over memory skills in the creation of bodies of knowledge that can be abstracted from a given problem scenario for future application.

The process of problem-solving itself is a key component in problem-based learning. Solving a problem is contingent on the formation of a problem space and the search for an appropriate solution path within said problem space. This process is influenced by both factors internal to the problem solver, in terms of their existing knowledge, skills, and experience, and external, in terms of the characteristics of the problem.

Designing a problem-solving task for problem-based learning thus requires the problem-solver's existing knowledge of the problem domain to be taken into consideration. Issues of authenticity also need to be addressed in relation to the type of information and medium used to provide it with respect to the real world problem being modelled. The manner in which this information is represented within the problem statement also needs to be contemplated.

Factors that mediate problem-based learning need to be considered during design in order to ensure that learning is directed towards satisfying the learning objectives that have been specified. Control of the learning process should be determined in accordance with learners' existing knowledge and understanding of problem-based learning. A facilitator is used to help guide the learning process in scenarios where the learner does not exercise complete control. The degree of learning control dictates the extent to which the learner determines what they learn, how responsible they are for the acquisition of information used to solve the problem, and the orientation of assessment between process, and outcome and context based evaluation. Feedback and opportunities for reflection should also be provided in order to support the search for a solution to the problem and the development of transferable knowledge.

Problem-based learning can harness computer technology to facilitate the learning process and support its various components and phases. Computer technology offers a number of potential benefits in this regard and can be utilised to create realistic, authentic, and engaging learning environments. This is especially relevant when knowledge transfer between problem scenarios is desired, whereby concepts learned in one context can be transferred and applied in another where the same concepts are required for resolution. Problem-based learning emphasises high

road transfer, which is the intentional mindful abstraction of information from one context and application in a new context, in order to transfer knowledge and concepts to future problem scenarios. The next section will discuss how computer simulations can be used within a problem-based learning framework to transfer accumulated knowledge to real world problem scenarios.

2.2 Learning Transfer with Computer Simulations

Simulations represent real world systems, and help foster the transfer of knowledge that provides insight into the behaviour being modelled (McHaney, 1991; Towne, 1995). The success of a simulation is often measured based on knowledge transfer and is only of value if the skills addressed and improved upon in the simulation environment are required in the operational environment that is being modelled (A. L. Alexander, Brunye, Sidman, & Weil, 2005). It is the contention of this research that computer-generated 3D simulation environments are a valid means of representing real world environments for the purpose of transferring knowledge that is accumulated during problem-based learning.

Applying computer simulations in problem-based learning environments requires an understanding of how learning transfer in real world systems can be facilitated (Chittaro & Serra, 2004; Dalgarno, Hedberg, & Harper, 2002; Withers, 2005) including:

- The situated nature of learning (Chapter 2.2.1), and;
- The identification of aspects common to both situated learning and problem-based learning, and the integration of components for guiding problem-based learning within the simulation environment (Chapter 2.2.2).

Facilitating learning transfer with computer simulations further necessitates the identification of an appropriate learning theory in which to ground problem-based learning within these environments. A subsequent discussion of constructivist learning theory identifies key assumptions common to situated learning, problem-based learning, and learning within simulation environments, with further discussion encompassing different interpretations of constructivism in relation to the nature of knowledge and the manner in which it is constructed within a problem-based learning environment (Chapter 2.2.3).

2.2.1 Situated Cognition

Situated learning draws from Brown, Collins and Duguid's (1989) theory of situated cognition, which contends that knowledge is situated within the activity, context and culture in which it is developed and used. Learning of this nature is relevant to the use of simulations in the development of performance expertise, as learning is best achieved, has a greater chance of application, and is most likely to transfer when it is situated in an environment which shares the operational goals of the system being modelled (Dobson et al., 2001). Thus, situated learning is contextual learning occuring in environments that are authentic, rather than decontextualised (Keh, Chang, Lin, & Hsu, 2005). Based on these contentions, it can be surmised that learning transfer is most effective between environments that share a common activity, operation, or learning goal, and are similarly related in terms of context and culture.

Activities are integral to cognition and learning, where learning should be embedded in activity in order to make deliberate use of the social and physical context of the environment (Brown et al., 1989). When learning is situated within a community of practice, the development of knowledge and the competence to perform well at an enterprise are manifestations of the active interplay between experience and ability (Dobson et al., 2001, p. 548). In essence, situated learning requires authentic contexts, activities, and assessments coupled with guidance based on expert modelling, situated mentoring, and legitimate peripheral participation (Dede, B Nelson, Ketelhut, Clarke, & Bowman, 2004; T. C. Reeves et al., 2002). Situated learning endeavours to construct contextual, real-life and highly interactive practice environments that can simulate real-life situational learning (Keh et al., 2005).

Situated learning also embodies aspects common to problem-based learning. Problem-solving activities are situated within the particular problem domain and are reliant on the cognitive operations that are specific to it (Jonassen, 2000; Smith, 1988). Feedback, both internally and externally, is of paramount importance to situated learning as it dynamically shapes the formation and content of knowledge (Clancey, 1997). Situated learning also stresses reflection on experience in order to facilitate changes in behaviour (Keh et al., 2005). Problem-based learning is fundamentally congruent to situated cognition, as both emphasise an authentic task or "problem" in context:

> Students have to be in the situation to conceive of new knowledge, to form new theories, and to apply that knowledge. On the other side, when we are in a

difficult situation we are in the very position to be compelled to resolve our
problem; reflecting on the problem, may thus result in the gaining of new
knowledge. When faced with a new problem, individuals weave what they
know about solving other problems and information about the new problem into
a coherent approach that transforms the novel problem into a more familiar
problem. The thinker makes use of whatever is familiar in the context of the
new problem to apply information and skills available from familiar problems
in bridging a solution to the novel problem (Hung, 2002, p. 403).

2.2.2 Learning with Simulations

The concept of learning being dependent on the negation of meaning through practice (Dobson
et al., 2001) is consistent with the ideas set forth in simulation based learning theory regarding
the importance of setting tasks or objectives as part of the learning process (Tait, 1994).
Learners need to be scaffolded in their pursuit of learning objectives and cannot be left
completely self-directed in this undertaking (Withers, 2005). Learners are not always capable of
handling their own learning process and may encounter problems relating to the statement of
hypotheses, the design of experiments, data interpretation, and the regulation of the learning
process where guidance is not present (de Jong et al., 1998). The free exploration of a 3D
simulation environment with no explicit task advice is unlikely to lead to learning advantages
over other instructional formats (Dalgarno, 2004).

There is a distinct need for simulation environments to be used within an instructional
framework in order for them to fulfil an instructive role in a satisfactory manner (Tait, 1994; van
Rosmalen, 1994; Withers, 2005). By utilising a problem-based learning framework in this
capacity, learners can be directed towards solving problems within the simulation environment
in an effort to fulfil specified learning objectives and accumulate knowledge that can be applied
to future problem scenarios in the real world. Simulations and problem-based learning share
common goals in that they are both directed towards the application of knowledge and concepts
to new situations; one via representational transfer and the other via mindful abstraction. Thus,
simulation environments can be used to enhance the potential for high road transfer inherent in
problem-based learning via their application within this pedagogical framework.

The instructional framework that a simulation is used within needs to be interwoven into the
simulation environment itself, such that the interface serves two functions; allowing the learner

to operate the simulation, and helping the learner to learn from using the simulation (van Rosmalen, 1994; Withers, 2005). Integrating the instructional framework into the simulation environment reduces the learner's demand on working memory, and in turn cognitive load (Sweller, van Merrienboer, & Paas, 1998). A simulation environment using a problem-based approach to learning would therefore be required to support the components of problem-based learning in this manner. Provision for the design and format of authentic real world problem scenarios would similarly need to be catered to. Additionally, opportunities and support for feedback and reflection would need to be provided in addition to flexible capabilities for control of the learning process, provision of learning resources, and orientation of assessment.

The technologies used to construct 3D simulation environments are capable in this regard. Problem presentation can be immediate, rich, and detailed, where processes related to a given problem can be integrated using the simulation environment's ability to model and execute complex relationships and decision rules (Hallinger, 2005; Hoffman & Ritchie, 1997). In this manner, learners can experience embodied problem situations which allow them to engage in discovery processes and foster their problem-solving ability (Chen-Chung, Yuan-Bang, & Chia-Wen, 2011). Furthermore, gaming technologies can be utilised in the development of 3D simulation environments to promote authentic and realistic learning experiences whilst providing flexibility for the design of different problem-solving scenarios (Beaumont, Savin-Baden, Conradi, & Poulton, 2012).

2.2.3 Constructivism

Situated learning and the provision of problem-based instruction relies on the ability of simulation environments to foster the development of learning via direct action within the instructional environment. This learning structure encourages active participation on behalf of the learner within the simulation environment, with an emphasis on *doing* rather than *collecting and processing* information (Withers, 2005). This experiential type of learning is one of the prominent features of constructivist learning theory, the key assumptions of which are summarised as follows (Merrill, 1991):

- Knowledge is constructed from experience;
- Learning is a personal interpretation of the world;
- Learning is an active process in which meaning is developed on the basis of experience;

- Conceptual growth comes from the negotiation of meaning, the sharing of multiple perspectives and the changing of our internal representations through collaborative learning, and;
- Learning should be situated in realistic settings; testing should be integrated with the task and not a separate activity.

Based on these assumptions, it is evident that constructivism shares characteristics in common with situated learning, simulation, and problem-based learning. Situated learning and the concept of negotiated meaning are key in both constructivist and situated cognition theories. Both of these theories also emphasise learning in realistic settings. Simulation-based learning theory and constructivism both stress integrated assessment. The active construction of knowledge based on personal experience is a key tenet in both problem-based learning and constructivism. These commonalities would suggest that constructivism makes for an appropriate philosophical foundation in which to ground simulation environments that exist within a problem-based learning pedagogy.

The experiential learning method in constructivism is also consistent with the exploratory nature of 3D simulation environments (Dalgarno & Lee, 2009; de Freitas & Neumann, 2009; de Jong et al., 1998; Harper, Squires, & Mcdougall, 2000; Winn, 1993). Constructivism and 3D simulation environments are well complemented in this regard as constructivism provides a philosophical foundation for activity within 3D simulation environments, whilst 3D simulation environments provide the perfect technology to apply constructivist theories in the "real world" (Mantovani et al., 2001). Simulation environments are popular with constructivists for two reasons: (1) they provide a realistic context in which learners can explore and experiment, and (2) the inherent interactivity allows learners to see immediate results as they create models or try out their theories about the concepts modelled (Rieber, 1992, as cited in Dalgarno, 2004). Such approaches provide opportunities for constructivist learning through their provision and support for resource-based, learner-centred settings and by enabling learning to be related to context and practice (Oliver, Harper, Hedberg, Wills, & Agostinho, 2002).

Within the field of constructivism, there are different opinions as to the nature of knowledge and the manner in which it is constructed. The degree of explicit instruction required depends on the learning domain, the specific learning outcomes, and the individual characteristics of the learner (Dalgarno, 2004). Three different interpretations of constructivism can be identified accordingly (Moshman, 1982, as cited in Dalgarno, 2004):

- Exogenous constructivism is the view that formal instruction, in conjunction with exercises requiring learners to be cognitively active, can help learners to form representations which they can later apply to realistic tasks;

- Endogenous constructivism emphasises the individual nature of each learner's knowledge construction process, and suggests that the role of the teacher should be to act as a facilitator in providing experiences which are likely to result in challenges to learner's existing models, and;

- Dialectical constructivism is the view that learning occurs through realistic experience, but that learners require scaffolding provided by teachers or experts as well as collaboration with peers.

It would appear that all three interpretations of constructivism are relevant to the research at hand. Problem-based learning requires learners to be cognitively active in the development of abstracted knowledge to apply to future scenarios, as in exogenous constructivism. True to endogenous constructivism, problem-based learning also emphasises the individual nature of knowledge construction and stresses the role of a facilitator in guiding this process. Dialectical constructivism is also consistent with problem-based learning in that learning occurs through exposure to real world problems and that scaffolding is required in order to guide the learning process. Some key distinctions between exogenous, endogenous, and dialectical constructivism are summarised in Table 2.10 as follows (Woolfolk, 1988, as cited in Tootell & McGeorge, 1998):

Table 2.10. Views of learning according to exogenous, endogenous and dialectical constructivism

	Exogenous constructivism	**Endogenous constructivism**	**Dialectical constructivism**
Knowledge	Fixed body of knowledge to acquire, which is stimulated from the outside world. Prior knowledge influences how information is processed	Changing body of knowledge, which is individually constructed in the social world. Knowledge is built upon what the learner brings with them	Socially constructed knowledge, which is built upon what participants contribute and construct together
Learning	Acquisition of facts, skills, concepts, and procedures, which occurs through the effective application of learning strategies	Active construction and restructuring of prior knowledge, which occurs through multiple opportunities and diverse processes to connect to what is already known	Collaborative construction of socially defined knowledge and values, which occurs through socially constructed opportunities
Teaching	Transmission. The teacher	Challenge and guide thinking	Co-construct

	guides students towards more accurate and complete knowledge	towards a more complete understanding	knowledge with students
Role of the teacher	The teacher teaches and models effective learning strategies and corrects misconceptions	The teacher acts as a facilitator and guide, listening for student's current conceptions, ideas, and thinking	The teacher acts as a facilitator, guide, and co-participant to co-construct different interpretations of knowledge and listen to socially constructed conceptions
Role of peers	Not necessary, but can influence information processing	Not necessary, but can stimulate thinking and raise questions	Ordinary part of process of knowledge construction
Role of student	Active processor, organiser and reorganiser of information. Strategy user and rememberer.	Active construction (within mind). Active thinker, explainer, interpreter, and questioner.	Active thinker, explainer, interpreter, and questioner. Active social participator.

Being that this research is concerned with the accumulation of knowledge that arises via individualistic problem-based learning and its subsequent application to real world problem scenarios, the endogenous interpretation of constructivism is the most appropriate. Endogenous constructivism focuses on internal, individualistic constructions of knowledge which are advanced via the revision and creation of new understandings out of existing ones (Applefield, Huber, & Moallem, 2001). This perspective emphasises individual knowledge construction stimulated by internal conflict as learners strive to resolve mental disequilibrium, such as that which arises during the process of solving problems (Applefield et al., 2001). Endogenous constructivism is represented diagrammatically in Figure 2.5:

Figure 2.5. Endogenous constructivism (Doolittle, 1998)

Figure 5 does not include any representation of external reality, as the endogenous interpretation of constructivism presupposes that external reality is not knowable (Doolittle, 1998). As such, endogenous constructivism can be situated within the context of the problem-solving process, after the point at which the internal and external factors affecting problem-solving have been taken into consideration.

2.2.4 Summary for Learning Transfer with Computer Simulations

The success of a computer simulation rests in its ability to facilitate the transfer of knowledge that is learned within the virtual environment to the real world environment that is being represented. The ability to transfer knowledge in this fashion is contingent upon learning within the simulation environment situated within the real world activity, context and culture in which it is developed and used. Learning within a simulation environment also needs to be guided by an appropriate instructional strategy such that learning is directed towards the achievement of designated learning objectives. In this manner, the simulation environment can be used within an instructional framework such as problem-based learning so that learners develop their knowledge and understanding as a result of using the simulation. This type of learning is

consistent with the experience based, learner centred nature of constructivism.

The consistencies between endogenous constructivism, problem-based learning, simulation-based learning and situated learning indicates that knowledge transfer between a simulation environment and a given real world problem scenario is dependent on active, experiential-based learning that is situated within an authentic representation. This authenticity is contingent on a valid delineation of the activity, context, and culture of the real world problem scenario by the simulation environment. Learning needs to be embedded within a problem-based framework in order to foster the high road transfer that this type of learning provides. Simulation environments are used to this end to provide an authentic foundation for the design and format of problem scenarios relative to real world problems, whilst also providing a platform for the implementation of the components of problem-based learning that guide and control the learning process. The key contributing factors to problem-based learning provided by simulation environments can thus be derived as the authentic representation of a given real world problem scenario, the ability to situate learning in problem-solving tasks that are modelled on real world problem-solving scenarios, and the ability to integrate provisions necessary for problem-based learning into the simulation environment. These contributing factors identified from a review of the literature are summarised along with pertinent evaluation criteria in Table 2.11:

Table 2.11. Contributing factors of simulation environments to problem-based learning

Factor	Criteria for evaluation
Authenticity of the simulation environment	· Physical fidelity · Functional fidelity
Situated problem-solving tasks	· Situatedness relative to the real world problem
Integrated support for problem-based learning	· Degree to which control factors of problem-based learning (see Table 9) are integrated into the simulation environment

2.3 3D Environments

Having explored problem-based learning and the manner in which computer-generated simulation environments can be used within this pedagogical framework to foster the transfer of knowledge to real world problem scenarios, it is now pertinent to explore the role of 3D environments in representing real world spaces. This examination is conducted with respect to the nature and function of simulations and a comparison of the characteristics of 3D

environment technologies to real world environments. The capability of 3D environments based on gaming technology to act in this capacity are also examined in relation to facilitating problem-based learning.

Examining computer-generated 3D environments requires an evaluation of their capacity to represent real world environments at a physical and functional level and convey information (Chapter 2.3.1) (Di Caro, 2003; Melo et al., 2011; Munro, Breaux, Patrey, & Sheldon, 2002; Towne, 1995). This was followed by an investigation of the technical capabilities of gaming technologies to act within this capacity with particular reference to FPS games (Chapter 2.3.2) (Dwyer, Griffith, & Maxwell, 2011; Germanchis, Cartwright, & Pettit, 2005; Lewis & Jacobson, 2002; Slater, Linakis, Usoh, & Kooper, 1996; Stone, Panfilov, & Shukshunov, 2011):

2.3.1 3D Environments as Simulations

From an instructional perspective, a simulation can model any real or conceptual system in order to facilitate a learning objective (Mason & Rennie, 2006). Simulations can represent a variety of different scenarios, from a highly detailed, microscopic view of a small part of a system, to a broad macroscopic view of a system as a whole. The methods used to represent systems can also vary, from simple text-based models to a fully immersive virtual environments. Irrespective of the manner in which a simulation models a system, the goal remains to represent system behaviour and respond to user action where knowledge accumulated in the simulation environment can be transferred to the real world system being modelled (Towne, 1995).

With this in mind, it becomes important to determine which type of simulation environment to employ so as to effectively represent the behaviour of the system and respond to user actions in order to facilitate the transfer of knowledge. Many different cognitive factors play roles in the use of virtual environment applications, including issues related to perception, attention, learning and memory, problem-solving and decision making, and motor cognition, which need to be considered with respect to the types of information that are conveyed in the virtual environment (Munro et al., 2002). As this research is concerned with transferring knowledge that is accumulated during problem-based learning to real world problem scenarios, it is necessary that the simulation employed models the behaviour and faithfully mimics reactions within a real world three dimensional space. It is the contention of this research that a 3D environment is an appropriate choice in this regard.

This contention is justified by examining the individual components of a simulation with regard to 3D environments. A simulation consists of two components: (1) a perceptible and operable representation of the real system, and (2) an underlying system model that expresses the way in which the representation reacts to action upon it (Towne, 1995, p. xxv). This is consistent with measuring simulation environments in terms of physical and functional fidelity (Williams, 2003), or physical and psychological fidelity (Stone, 2008). Thus, we can determine the effectiveness of a 3D environment to simulate a real world space in accordance with the authenticity of the interface and underlying behavioural model.

The degree of fidelity required to perceivably represent a system depends on whether the representation needs to be highly realistic, and reflect the characteristics and properties of the real system with great accuracy, or merely at a level that suggests what happens in the real world (Towne, 1995; Wilson, 1997). Not all simulations require high fidelity environments, where the level of fidelity required should be determined with reference to the desired learning outcomes and the environment that is being modelled (A. L. Alexander et al., 2005). The physical reality of the learning situation is of less importance than the characteristics of the task design, and engagement of students in the learning environment (T. C. Reeves et al., 2002). As such, the level of fidelity required in a simulation environment is contingent on the nature of the learning task (Stone, 2008, 2011), as depicted in Figure 2.6:

Figure 2.6. Task elements and fidelity in 3D simulation environment design (Stone, 2008)

A simulation environment depicting realistic task elements that are fundamentally cognitive in nature requires high physical fidelity to maintain high psychological fidelity. This suggests that

a simulation environment employed within a problem-based learning framework requires a faithful and authentic representation of the appearance, operation, and behaviour of the real world problem scenario it depicts, as problems with greater fidelity are more likely to transfer to the real world (Norman, 1988). In virtual environments, there is an increased reliance on visual senses to provide information due to the fact that many other sensory cues are not present (Wilson, 1997). It is therefore logical to assume that the visual information presented by a 3D environment should be of high quality in order to compensate for the deficiency of information provided to the other sensory modalities. If other sensory modalities, such as sound, are to be stimulated within the simulation environment, then the extent of the auditory effect must match the visual image presented to the user, otherwise a mismatch between sensory cues may occur, compromising the credibility of the simulation (Stone, 2008).

The simulation of lighting conditions is one of the key aspects in creating a visually realistic representation of a real world environment (Loffler, Marsalek, Hoffman, & Slusallek, 2011). This is facilitated in 3D environments via the application of global (view-independent) and local (view-dependent) illumination methods which can be used to accurately recreate lighting conditions within real world spaces (Malhorta, 2002). Lighting sources in 3D environments can be categorised as dynamic or static, where dynamic lighting equations are calculated from active light sources that can move and have modifiable properties, while static lighting equations are pre-calculated using light maps which store lighting information as textures (Grohn, 2007; Kogler, 2003). Shadows are also used to provide depth, perspective, and spatial cues and are a very important dimension in the perception of realism in 3D environments (Drettakis, Roussou, Tsingos, Reche, & Gallo, 2004; Knecht, Dunser, Traxler, Wimmer, & Grasset, 2011; Malhorta, 2002).

The ability to texture models and other geometric shapes also allows 3D environments to enhance the sense of visual realism in relation to the real world system being modelled (Shiratuddin & Thabet, 2011; Stytz, Banks, Garcia, & Godsell-Stytz, 1997). Photorealistic textures can be used for this purpose to enhance the perceived detail in simple geometric models provided that there are no correspondence issues between the texture and the geometry (Colburn, Agarwala, Hertzmann, Curless, & Cohen, 2012; Gruber, Pasko, & Leberl, 1995). For example, a study performed by Peruch, Belingard, and Thinus-Blanc (2000) indicated that spatial learning was affected by the amount and/or quality of information available in a virtual environment, where direction and travel distance errors were smaller in environments that featured textured geometric shapes, as opposed to untextured ones. Similarly, a study by

Bonneel, Suied, Viaud-Delmon, and Drettakis (2010) demonstrated that the level of visual detail within a virtual environment had a noticeable effect on material perception.

The potential for realism inherent in 3D environments can establish a greater sense of presence (Dalgarno, 2004; Dalgarno & Hedberg, 2001; Psotka, 1995; Schrader & Bastiaens, 2012). This has the ability to facilitate a greater transfer of knowledge, as presence increases the likelihood of users' behaviour in the virtual environment to be consistent with the real world environment that is being modelled (Slater et al., 1996). Virtual environments take advantage of the imaginative ability of people to "psychologically transport" their "presence" to another place that may not exist in reality, attending to it at the exclusion of one's surrounding environment (Sadowski & Stanney, 2002a). The potential for realism in 3D environments facilitates this "transportation" as it focuses the user's attention within the virtual environment, enhancing involvement and thereby increasing the psychological perception of existence within the virtual space (Sadowski & Stanney, 2002a, 2002b). Sadowski and Stanney (2002a) provide a set of characteristics that contribute to the perception of presence in virtual environments, which are listed together with corresponding design guidelines and issues in Table 2.12:

Table 2.12. Guidelines for supporting presence in virtual environments (Sadowski & Stanney, 2002a, p. 796)

Variable	Guideline	Issue
Ease of interaction	Provide seamless interaction such that users can readily orient in, traverse in, and interact with the virtual environment.	Poorly designed interaction takes focus away from the experience and places it instead on motion/mechanics.
User-initiated control	Provide immediacy of system response, correspondence of user-initiated actions, and a natural mode of control.	Delays, discordance of users' versus effectors actions, and unnatural control devices hinder engagement in a VE.
Pictorial realism	Provide continuity, consistency, connectedness and meaningfulness of presented visual stimuli.	Poorly designed or displayed visual interactions may hinder engagement in a VE.
Length of exposure	Provide sufficient exposure time to provide VE task proficiency, familiarity with a VE, and sensory adaptation.	Avoid unnecessarily prolonged exposures that could exacerbate sickness.
Social factors	Provide opportunities to interact with and communicate with others verbally or by gestures. Provide confirmation that others	If one's presence in a VE is not acknowledged by

	recognise one's existence in a VE.	others, it may hinder the perception that they "exist" in the environment.
Internal factors	Identify the types of individuals who will use a VE system and their preferred representational system (i.e., visual, auditory, kinesthetic).	Individual differences can render VE systems differentially effective.
System factors	Provide head tracking, a large field of view, sounds, stereopsis, increasing update rates, multimodal interaction, and ergonomically sound sensors/effectors to facilitate presence.	Poorly designed systems can degrade users' experience. Note: This does not suggest that "extreme realism" is required, but rather what is provided should be well designed and developed.

Facilitating a sense of presence within a virtual environment is also contingent on the provision of stimuli and responses consistent with those contained within the real world environment being modelled (R. Schmidt & Young, 1987). The concept of learning transfer being reliant on the relevance and authenticity of the stimuli and response of the simulation environment is consistent with Williams' (2003) measure of a simulation in terms of its physical and functional fidelity.

Having acknowledged the potential of 3D environments to represent real world spaces on a perceptible level, it is necessary to assess 3D environments in terms of their ability to operate and behave consistently with real world space. Examining Williams' (2003) descriptions of physical and functional fidelity, this includes the manipulation and feedback of the interface, as well as the modelling of behavioural responses within the virtual environment.

For any given simulation, the behaviours modelled within the virtual environment must be contingent on the particular learning outcomes and goals in mind, as it is infeasible and inefficient to model all possible scenarios within a simulation environment (Wilson, 1997). This research is concerned with facilitating the transfer of knowledge accumulated within a virtual problem-based learning environment existing as a representation of a real world problem scenario. As such, behaviours, relationships, and interactions between components in the virtual environment need to be appear faithful to their real world counterparts in order to maintain the authenticity of the simulation. Two aspects that are fundamental in the representation of real world environments in this regard are the physical properties of the real world environment itself and the manner in which an individual moves throughout it. The key characteristics of 3D

environments which facilitate the representation or real world systems can thus be identified as follows (Dalgarno & Hedberg, 2001; Merchant et al., 2012):

- An environment modelled using 3D vector geometry, meaning that objects are represented using x, y and z co-ordinates, describing their shape and position in 3D space;
- Dynamic rendering of the user's view of the environment depending on their position in 3D space;
- Dynamic rendering of the user's view as the user moves freely through the environment, and;
- A minimum degree of interaction with some of the objects within the environment, in that they respond to user action (e.g. a button, door etc.).

Examining these characteristics, it is evident that 3D environments embody properties which are common to real world three dimensional spaces. Both environments use three dimensional Euclidean geometry to delineate the objects within them, and as such, 3D environments can be used to construct scale representations of real world spaces, given appropriate plans or schematics. As a result, dimensions, perspective and relative distances between objects within the virtual environment can be consistent with those in the real world. This allows users to develop spatial representations, which describe the relative locations and attributes of phenomena in order to support movement, wayfinding, and navigation (Downs & Stea, 1973; Lynch, 1960; Siegel & White, 1975; Tversky, 2000), of the virtual environment that are applicable to the real world environment that is being modelled.

The dynamic rendering characteristics of 3D environments provide immediate visual feedback to the user and, combined with the 3D vector geometry environment model, create the illusion of free movement within the virtual environment. This is achieved via the rotation and translation of the user's viewpoint within the 3D model in accordance with the manipulation of the mouse, keyboard or joystick in a desktop 3D environment. This ability allows users to freely look and move throughout a 3D virtual environment in a manner consistent with a three dimensional real world space.

The degree of interaction with objects required within the environment is typically dependent on the learning outcome and the real world environment being modelled (D. Jonassen, Howland, Moore, & Marra, 2003). In typical 3D environments, the user is able to interact with the

environment simply by looking around or moving within it, with the display updating accordingly. This provides the base level of functionality for problem scenarios which require movement and orientation within a three dimensional space. Additional functionality, such as explicit interaction with specified objects or areas of the environment, can be provided via scripted elements or other programming constructs, such that user interaction with an object can initiate a state change in the object and trigger a perceivable response, as appropriate.

The ability of 3D simulation environments to authentically represent three dimensional spaces physically and functionally enables them to be particularly adept at conveying certain types of information to the user. The major types of information that can be presented in a 3D simulation environment comprise locational knowledge, structural knowledge, behavioural knowledge, and procedural knowledge, which are summarised as follows (Munro et al., 2002):

- *Locational knowledge* – Many virtual environments allow users to change their location and orientation freely while observing objects within the environment. This type of experience can provide the user with a richer set of information regarding the relative location of simulated objects, how to get to a location, and how to bring objects into view, access, and manipulate them.
- *Structural knowledge* – Virtual environments have the potential to convey a rich variety of structural information, which details the manner in which concepts within a domain are interrelated. Structural knowledge can define relationships between objects within the environment, where an object can exist as a component part of another object, supportive or dependent on other objects, or contained within another object.
- *Behavioural knowledge* – Virtual environments can effectively convey information detailing interaction amongst objects and the user within the environment. This includes knowledge of cause-and-effect state changes, the application or use for given objects, and the principles that explain the behaviour of whole classes of objects.
- *Procedural knowledge* – Virtual environments may be appropriate for conveying knowledge of how to carry out procedures. This can be especially useful for tasks where a number of different action sequences may lead to the desired goal, but a specific set is preferred due to reasons of cost-effectiveness, speed, or safety, for example. Procedural knowledge can include knowledge of task prerequisites, knowledge of the goal hierarchy of required action sequences, and knowledge of the action sequences themselves, particularly those that require movement or orientation changes in three dimensions.

The capability to depict locational, structural, behavioural, and procedural knowledge prescribes 3D simulation environments to a number of cognitively appropriate tasks. These tasks include navigation and locomotion in three dimensional environments, learning abstract concepts with spatial characteristics, manipulation of complex objects and devices in three dimensional space, as well as decision making (Munro et al., 2002), all of which are of integral relevance to this research.

2.3.2 Gaming Technologies

Computer games share the same technological parentage as military simulations, though the development of each industry has been remarkably different (Herz & Macedonia, 2002). Although early game development lagged behind its military sibling due to a lack of financial and institutional support, the gaming industry has nonetheless thrived, with modern estimates of revenue exceeding those of the Hollywood box office (Branch, LaBarre, & Szabo, 2006; Snider, 2003). The growth in popularity in games and gaming culture has fuelled an unparalleled period of technological development, where computer games have expropriated the best in hardware and software for themselves, resulting in the most sophisticated, responsive and interactive simulations being built by the engines used to power games (Lewis & Jacobson, 2002). Improvements in video game technologies have greatly increased the possibility of creating extremely involving interactive virtual environments with enhanced exploratory choices in immersive experience (Catanese, Ferrara, Fiumara, & Pagano, 2011).

This development has given rise to the concept of *serious games*, which is "the application of gaming technology, process, and design to the solution of problems faced by businesses and other organisations" (Susi, Johannesson, & Backlund, 2007, p. 7). For serious games, it is essential that the most important elements of learning are in focus, and that the assumptions necessary for making a simulation workable are correct, otherwise the simulation will teach the wrong kind of skills (Susi et al., 2007).

Simulations based on gaming technology have been employed in fields including defence (Bonk & Dennen, 2005), medicine (Depledget et al., 2011; McGrath & Hill, 2004; Stone, 2011), mining (Tichon & Burgess-Limerick, 2011), and architecture (Schroeder, 2011). The use of gaming technology in such a wide variety of applications has been driven in large part by the development of the game engine; a modular, general purpose component of code which allows content and functionality to be separated, and thus adapted to a range of different purposes

(Lewis & Jacobson, 2002). Game engines consist of a collection of code modules responsible for scripting, imagery, rendering, artificial intelligence, physics, animation, network communication, and resource management (Lewis & Jacobson, 2002; Navarro, Pradilla, & Rios, 2012). They are abstracted from game logic and level data modules, and are capable of working with different asset libraries (sets of models, textures and sounds), allowing developers considerable flexibility. Game engines are typically bundled with development tools, software development kits and built-in scripting languages (Dupire, Topol, & Cubaud, 2005; Navarro et al., 2012) which remove the need for intimate programming knowledge of 3D graphics Application Programming Interfaces (API) such as OpenGL and Direct3D, greatly simplifying the development process. 3D First Person Shooter (FPS) game engines in particular, have exhibited the most development in terms of visual quality (Germanchis et al., 2005; Stone et al., 2011), and are subsequently of importance to this research.

With regard to simulating real world three dimensional spaces realistically, one of the most significant aspects of the game engine is the rendering module (often referred to as the rendering
engine). Lewis and Jacobson (2002, p. 29) identify this as the "crown jewel" incorporating all of the complex code needed to efficiently identify and render the user's view from a complex 3D environment model. This code is heavily optimised and refined to deliver an acceptable minimum number of frames per second, which is generally required to be anything over fifteen (Dalgarno et al., 2002; Farrell et al., 2003) to thirty frames per second (Wilson, 1997) in order to provide a smooth and interactive experience. Frame rates are an important visual heuristic within 3D environments as insufficient frame rates discourage discovery and investigation of the environment (Dupire et al., 2005). Furthermore, insufficient frame rates reduce immersion, which describes the extent to which a computer system, particularly its mechanism for the display of visual information, is extensive, surrounding, inclusive, vivid, and matching:

> The displays are more *extensive* the more sensory systems that they
> accommodate. They are *surrounding* to the extent that information can arrive at
> the person's sense organs from any (virtual) direction, and the participant can
> turn towards indicating that direction receiving the appropriate directional
> sensory signals. The notion of surrounding also includes the greater the
> reproduction of the natural modes of sensory presentation (visual and auditory
> stereopsis for example). They are *inclusive* to the extent that all external sensory
> data (from physical reality) is shut out. Their *vividness* is a function of the

variety and richness of the sensory information they can generate (Steuer, 1992). Vividness is concerned with the richness, information content, resolution and quality of the displays. Finally, immersion requires that there is a *match* between the participant's proprioceptive feedback about body movements, and the information generated on the displays. A turn of the head should result in a corresponding change to the visual display, and, for example, to the auditory displays so that perceived sound direction is invariant to the orientation of the head. *Matching* requires body tracking, at least head tracking, but generally the greater the degree of body mapping, the greater the extent to which the movements of the body can be accurately reproduced. (Slater et al., 1996, p. 3).

According to this criteria, standard desktop personal computers do not exhibit as much potential for immersion as other forms of virtual environment technology, such as the head mounted displays used in virtual reality environments. Modern desktop displays could not be considered as being extensive or particularly surrounding, although many FPS game engines do include provisions for three dimensional sound and directional audio. However, desktop computers utilising FPS technology do exhibit potential for vividness in their ability to depict three dimensional environments at a high visual quality. Creating a more immersive environment in this manner therefore requires increased load on the rendering hardware in the form of greater environmental quality and detail. 3D FPS game engines are particularly well suited to providing high levels of visual detail at an acceptable frame rate, as they are designed to handle the high visual and performance demands placed upon them by gamers.

The suitability of 3D FPS game engines to realistically represent real world spaces is further demonstrated in examining other applications of the technology outside of gaming. In their study on geospatial virtual environments, Gernmanchis, Cartwright and Pettit (2005) used the FarCry game engine to model a virtual representation of a large-scale urban environment. A 3D FPS game engine was selected because it offered a 'more interactive, realistic and hence a more engaging environment' (Germanchis et al., 2005, p. 1). Similarly, Shiratuddin and Thabet (2002) used the Unreal Tournament game engine to create an office walk through for visualising construction projects, while Fuchs and Leighton (2011) used the UT2004 game engine to model a Tudor Manor for heritage education. A common set of characteristics for 3D FPS game engines that facilitate the modelling of a virtual representation of a real world environment can be identified from these studies and include:

- Ability to model a true 3D environment, including objects, architecture, and landscape;
- Allows the user real-time movement around the virtual environment. Collision detection within the environment is built in;
- Allows the user to interact with the model, facilitated by the immediacy of the system to respond to user actions at a realistic frame rate;
- Offers powerful graphics quality without diminishing performance to an unsatisfactory level, and;
- Realistic environment visualisation achieved via photo-realistic texturing, real-time dynamic lighting, shadows, real-time reflective and mirrored surfaces, colours, and shade variances.

3D FPS game engines are sufficiently capable of delivering a high fidelity, realistic representation of a real world environment on an inexpensive desktop computer system. Users are able to move freely throughout a virtual environment and interact with the environment itself and the objects within it, the behaviours and presence of which can be specified using the accompanying scripting and development tools. Furthermore, these scripting tools and other programmable constructs inherent in 3D FPS game engines also provide a mechanism for built in "score keeping" for after action review, which provides a valuable means for measuring user performance (McGrath & Hill, 2004). Performance measurement provides a basis for making intelligible comparisons involving the virtual environment system, and is an important element in providing meaningful feedback and knowledge of the results of actions to individual users (Lampton, Bliss, & Morris, 2002). Daemons, which monitor the state of the simulation environment and changes its instructional state once a certain, pre-specified simulation state has been reached, can be utilised for this purpose:

> Daemons can be created to monitor the experiments learners perform, the hypotheses they state, and the way they respond to questions. As daemons set an instructional state, the environment can react to these small learner models. This introduces an agent-like means of learner modelling where small daemons watch aspects of the learner behaviour. As daemons can be turned on and off during a session, the sophistication of the learner model can be adapted to the actual needs in a given situation (de Jong et al., 1998, pp. 242–243).

The use of daemons allows feedback to be provided in response to specific learner actions within the simulation environment. Furthermore, it permits the creation of a flexible facilitator

type construct, which can be directed to pose predefined questions to the learner, call for certain content to be displayed, or put the simulation into a certain state under specific circumstances which are triggered in response to input or changing system wide variables (Munro et al., 2002). The questions posed by facilitators play an important role in guiding the problem-based learning process (Barrows & Tamblyn, 1980; Hmelo-Silver, 2004; Savery & Duffy, 2001), and the application and viability of intelligent tutoring systems within simulation environments has been demonstrated in several different studies (de Antonio, Ramirez, & Mendez, 2005; Koedinger, Suthers, & Forbus, 1998; Stiles & Munro, 1998).

These characteristics, combined with the comparatively low-cost (McGrath & Hill, 2004; Orr et al., 2003; Topolski, Green, Leibrecht, & Rossi, 2011) and over the counter availability (Bouchard et al., 2012; Stone, 2008), make 3D FPS game engines an ideal application for developing 3D simulation environments within a problem-based learning framework on a standard desktop computer system.

2.3.3 Summary for 3D Environments

It has been argued that 3D environments based on FPS game engines are a valid means for simulating real world environments based on their ability to represent three dimensional spaces at a high visual quality whist maintaining a frame rate that allows the user fluid control of the virtual environment. The potential for high visual fidelity inherent in this type of environment can be used to depict a realistic virtual space where the behaviour of objects and their subsequent relationships with each other and the user can be represented appropriately, whilst also providing the user with a sense of presence and immersion. 3D environments based on FPS gaming technology are well-suited to the representation of real world tasks that may involve movement and orientation, complex object manipulation, or decision making in a three dimensional space. Furthermore, the scripting languages and other programmable constructs inherent in FPS game engines provide the ability to develop 3D simulation environments within a problem-based learning framework, where assessment, feedback, control and guidance of the learning process, and appropriate learning resources can be provided. The key contributions to problem-based learning provided by 3D environments based on FPS gaming technology identified from the literature can thus be established as three dimensional representation, high visual fidelity, immediate system response, and user control. These are summarised along with corresponding evaluation criteria in Table 2.13:

Table 2.13. Characteristics of 3D environments based on FPS gaming technology which contribute to problem-based learning

Factor	Criteria for evaluation
Three dimensional representation	· Three-dimensional representation of the environment · Extent to which knowledge is effectively communicated
High visual fidelity	· Quality of visual elements · Richness of information content · Perceived sense of immersion · Perceived sense of presence
Immediate system response	· Perceived immediacy of system response to input · Consistency of frame rate · Perceived sense of presence
User control	· Support for movement and interaction · Perceived sense of presence · Quality of collision detection

2.4 The SUPL Design Framework:

A Design Framework for Problem-based Learning Transfer using 3D Simulation Environments based on Gaming Technology

A review of the literature was undertaken in order to explore how 3D simulation environments could be used to develop knowledge and skills for resolving real world problems. This review encompassed three key areas – problem-based learning, learning transfer with computer simulations, and 3D environments, with a view towards establishing design considerations for the development of problem-based learning environments that were relevant to this enterprise. The following paragraphs provide a summary of the key areas of the literature which informed the synthesis of these design considerations.

Problem-based learning is a learner-centred, experiential based pedagogical framework that emphasises problem-solving in the development and accumulation of knowledge. Solving a given problem requires the problem-solver to develop an internal representation of the problem, referred to as the problem space, which is subsequently searched in order to locate an appropriate solution path. The process of forming and searching the problem space for a solution is contingent on both the individual differences of the problem solver as well as the

variable characteristics of the problem-solving task and the manner in which it is represented. The problem-solver's degree of prior, domain, and structural knowledge, as well as their general problem-solving skills (Chapter 2.2.3.1), affect their perception, identification, and isolation of the important characteristics of a given problem, as well as their ability to form them into an effective mental representation. These attributes also determine the subsequent search strategies that are employed by the problem-solver within the problem space in locating a solution.

The characteristics of the problem-solving task, which include its structuredness, complexity, and domain specificity, and the manner in which it is represented to the problem-solver are also important factors in determining the development of the problem space and the subsequent employment of search strategies (Chapter 2.2.3.2). Where the problem-solving task facilitates the development of knowledge for a contextually similar problem, the situatedness of the problem-solving task at hand is important in order for knowledge and skills to be transferable. The facilitation of knowledge transfer between contextually similar problems also requires that issues of authenticity are addressed regarding the type of information that is conveyed to the problem-solver and the manner in which it is presented. The representation of the problem-solving task is key in this regard, where form, organisation, and sequencing of the problem-solving task influence the problem-solvers perception of the problem, their subsequent internal representation of the problem, and the problem-solving strategies they employ.

Computer-generated simulations can be utilised to provide an authentic foundation for the transfer of knowledge for real world problem scenarios whilst providing a platform for the implementation of components that mediate the learning process (Chapter 2.3). Simulations based on gaming technology are well suited to representing real world systems as they allow the objects that exist within them to be described and detailed in accordance with three dimensional Euclidean geometry (Chapter 2.4). Combined with the high visual fidelity that is inherent in these virtual environments due to the demands placed upon them by gamers, 3D simulation environments based on gaming technology are capable of authentically representing real world environments. Such virtual environments are well-suited to training, as users are given control over their movement and orientation in three dimensions to which the environment provides a sufficiently immediate response in order to maintain the illusion of movement and dynamic interaction. These characteristics founded upon gaming technology enable 3D simulation environments to effectively depict locational, structural, behavioural, and procedural knowledge and relationships, making them suitable for applications related to navigation, locomotion, and manipulation of objects and environments, as well as decision making

scenarios, in three dimensions.

In order to guide the learning process and the subsequent accumulation of knowledge, problem-based learning utilises a number of different control mechanisms in order to satisfy the learning objectives that have been specified (Chapter 2.2.4.4). The variable degree of control afforded to the learner over the learning process, which is determined with reference to the learner's prior learning and experience with the problem-based learning process, dictates responsibility for delineating the amount and sequence of information that is to be learned. This degree of control in turn influences the provision of learning resources and the orientation of assessment, which are used as a means of supporting the problem-solving process and determining whether the specified learning objectives have been successfully satisfied . The learner is also provided with feedback in response to their attempts to solve a given problem. This is an important aspect in shaping and refining their attempts at resolution that is also necessary for the transfer of knowledge and skills between contextually similar problems. The learner is also provided with opportunities for reflecting on their problem-solving experience where the knowledge accumulated as a result can be abstracted and applied to future problem-solving situations. The control mechanisms applied within a problem-based learning framework can be integrated into a 3D simulation environment based on gaming technology. Constructing a problem-based learning environment in this manner allows learners to become proficient with problem-solving tasks that are situated relative to real world problem-solving scenarios in an authentic and realistic three-dimensional environment. In this way, knowledge can be accumulated within a problem-based learning framework utilising a 3D simulation environment with the goal of transferring it to a corresponding real world problem scenario.

Design considerations can thus be synthesised according to the internal and external factors which affect problem-solving performance, the task and control considerations for problem-based learning, and the contributing factors of simulation environments and 3D gaming technologies to problem-based learning (Tables 2.3, 2.6, 2.8, 2.9, 2.11, and 2.13). The design considerations identified in these six tables can be classified into a more usable configuration as Situational Analytical Factors, Situational Design Considerations, and Problem-based Learning Design Principles according to their role in the design process:

- **Situational Analytical Factors** encompass factors which exist outside the control of the designer that need to be accommodated to facilitate knowledge construction and learning transfer within a 3D problem-based learning environment. This includes the

existing problem-solving knowledge of the user, the situatedness of the real world problem, and the technical capacity of the 3D simulation environment to represent the real world problem. These factors can be identified via situation analysis of the real world problem and subsequently used to inform the design of the 3D simulation environment.

- **Situational Design Considerations** are incorporated into the design of a 3D problem-based learning environment to accommodate the corresponding overlapping Situational Analytical Factors which have been identified during situation analysis. This includes the characteristics of the problem-solving task, the manner in which it is presented to the user, and the extent of interaction that the user is afforded. Situational design considerations need to strike a balance between the needs of the user, the nature of the real world problem-solving task, and the technical capacity of the 3D simulation environment to approximate real world problem-solving activity.

- **Problem-based Learning Design Principles** are the core tenants which guide the learning process. The principles of feedback, assessment, information, learner control, and reflection are characterised in conference with the Situational Analytical Factors and Situational Design Considerations that have been established.

The organisation of these design considerations can be framed using the framework for the design of technology-mediated learning settings developed by Oliver and Herrington (2001). Their framework embodies three critical components in the promotion of knowledge construction: the designation of *learning supports*, the selection of *learning tasks*, and the appointment of *learning resources*. Within this context, the user's existing problem-solving knowledge functions as learning supports. Similarly, the problem-solving task approximating real world problem-solving activity operates as learning tasks. Furthermore, the information provided for the user by the 3D simulation environment to solve the problem serves as learning resources. This suggests that the design considerations for directing problem-based learning towards the accumulation of knowledge for real world application can be organised in relation to (1) the user, (2) the problem-solving task, and (3) the 3D simulation environment.

Given this configuration, a Venn diagram appropriately details the arrangement of Situational Analytical Factors, Situational Design Considerations, and Problem-based Learning Design Principles. Consistent with Oliver and Herrington's framework (2001), three intersecting sets can be assumed for the user, the problem-solving task, and the 3D simulation environment. The Situational Analytical Factors, Situational Design Considerations, and Problem-based Learning

Design Principles established from the literature can be situated within these sets according to their role in the design process.

Situational Analytical Factors inhabit the outer, non-intersecting areas of each set as they represent the entry point to the design process. These design considerations acknowledge external contextual factors which govern the learning process and are identified during situation analysis. This includes the prior knowledge, domain knowledge, structural knowledge, and general problem-solving skills of the user, the situatedness of the real world problem, and the technical capabilities of the 3D simulation environment to approximate real world problem-solving activity via 3D representation, immediate system response, authenticity, and high visual fidelity.

Working inwards, Situational Design Considerations are located at the intersections between set pairs. This reflects their role in accommodating multiple Situational Analytical Factors in the design of the simulation. The structuredness, complexity, and domain specificity of the problem is designed to elicit the user's existing problem-solving knowledge whilst remaining consistent with the situatedness of the real world problem. Similarly, the problem representation and authenticity of information presented during the problem statement
is designed to reflect the situatedness of the real world problem given the technical capabilities of the 3D simulation environment. Likewise, mechanisms for user control are designed within the technical capabilities of the 3D simulation environment to elicit the user's existing knowledge of real world problem interaction.

Finally, the inner core and intersection point of all three sets contains the Problem-based Learning Design Principles which mediate the learning process. These design considerations build upon the Situational Analytical Factors and Situational Design Considerations established to assist the user to resolve the problem-solving task and develop knowledge for real world application using the technical capabilities of the 3D simulation environment. This includes the implementation of feedback to guide the user during problem-solving activity, the integration of assessment mechanisms for monitoring their performance, the furnishing of information within the 3D simulation environment to address the learning needs of the problem, the provision of a variable degree of learner control to invest users in the learning process, and the application of implicit and explicit prompts for reflective thinking.

The application of Oliver and Herrington's (2001) design framework for describing the

arrangement of Situational Analytical Factors, Situational Design Considerations, and Problem-based Learning Design Principles is thus detailed in Figure 2.7 . This is referred to as the Simulation, User, and Problem-based Learning (SUPL) design framework.

User
(learning supports)

Prior knowledge

Domain knowledge

Structural knowledge

General problem-solving skills

Structuredness

Complexity

Domain specificity

Feedback

Assessment

Information

Learner control

Reflection

User control

High visual fidelity

Authenticty of the simulation environment

Immediate system response

Situatedness

Problem representation

Authenticity of information

3D Representation

Problem-solving Task
(learning tasks)

3D Simulation Environment
(learning resources)

Situational Analytical Factors

Situational Design Considerations

Problem-based Learning Design Principles

Figure 2.7. The Simulation, User, and Problem-based Learning (SUPL) design framework

In order to address the efficacy of the SUPL Design Framework and address the research questions proposed by this study, evaluation criteria were derived from the literature to assess the impact of each design consideration. These evaluation criteria, previously detailed in Tables 2.3, 2.6, 2.8, 2.9, 2.11, and 2.13, are collated into a master set of evaluation criteria for each design consideration in the SUPL Design Framework in Tables 2.14, 2.15, and 2.16.

Table 2.14. Criteria for evaluating Situational Analytical Factors

Factor	Criteria for evaluation
Prior knowledge	· Previous experience with contextually similar problems · Identification of unknown entities in the problem · Evidence of learning transfer
Domain knowledge	· Identification of objects, events, and ideas relevant to the problem · Identification of information necessary for resolving the problem
Structural knowledge	· Identification of relationships in the problem domain
General problem-solving skills	· Reliance on general problem-solving skills · Specificity of the problem-solving strategy
Situatedness	· Situatedness relative to the real world problem
Three dimensional representation	· Three-dimensional representation of the environment · Extent to which knowledge is effectively communicated
Immediate system response	· Perceived immediacy of system response to input · Consistency of frame rate · Perceived sense of presence
Authenticity of the simulation environment	· Physical fidelity · Functional fidelity
High visual fidelity	· Quality of visual elements · Richness of information content · Perceived sense of immersion · Perceived sense of presence

Table 2.15. Criteria for evaluating Situational Design Considerations

Factor	Criteria for evaluation
Structuredness	· Extent of existing domain specific knowledge and general problem-solving skills · Perceived familiarity of the problem
Complexity	· Perceived uncertainty of the problem-solving context · Perception of related entities within the problem domain · Recognition of problem complexity
Domain specificity	· Perceived meaningfulness of the problem

	·	Problem-solving strategies employed
	·	Extent to which problem is contextualised
Authenticity of information	·	Consistency of information
Problem representation	·	Perception of the problem representation
	·	Identification of relevant problem features
	·	Identification of relationships
	·	Problem-solving strategies employed
User control	·	Support for movement and interaction
	·	Perceived sense of presence
	·	Quality of collision detection

Table 2.16. Criteria for evaluating Problem-based Learning Design Principles

Factor		Criteria for evaluation
Feedback	·	Perception and understanding of feedback
	·	Modification of user behaviour due to feedback
	·	Relevance of feedback
	·	Integration of feedback
Assessment	·	Validity of assessment
	·	Fidelity of assessment
	·	Integration of assessment
Information	·	Extent of information available
	·	Integration of information
	·	Application of information
Learner control	·	Control of the learning process
	·	Integration of learner control
	·	Suitability of learner control
Reflection	·	Identification and development of new knowledge
	·	Future applications of new knowledge
	·	Integration of reflection

Using the evaluation criteria detailed in Tables 2.14, 2.15, and 2.16 to assess the efficacy of each design consideration required the application of the SUPL Design Framework within a real world context. This methodological approach entailed the development of a 3D simulation environment to address real world training concerns within an underground mining environment. This is described in detail in the following chapter.

3 Methodology

The purpose of this research is to examine the effectiveness of 3D simulation environments built upon gaming technology to serve as platforms for facilitating problem-based learning concentrating on real world problem scenarios. This examination is conducted with reference to the evaluation criteria derived in Chapter 2.4 in a study conducted in association with Dominion Mining and their Challenger gold mining operation based in South Australia. A 3D simulation environment based on gaming technology, designated the Fires in Underground Mines Evacuation Simulator (FUMES), was designed and developed in order to satisfy training requirements identified by Dominion in accordance with a problem-based approach to learning.

3.1 Research Context

FUMES was designed to address real world training requirements at the Challenger mining facility. The efficacy of FUMES and the veracity of SUPL Design Framework were evaluated according to the ability of Challenger mining personnel to utilise and develop knowledge and skills that were necessary for successful emergency evacuation. Given the inherently embedded nature of the study in conjunction with the direct involvement of the researcher in designing FUMES, this demonstrates that action research and design-based research were suitable methodologies for the study.

While design-based research emphasises an iterative approach to design and implementation, the time constraints and financial limitations of the study imposed some restrictions in this regard. As only six months was allocated for the design and development of FUMES, this meant that subsequent design iterations beyond the initial implementation were not feasible. However, the findings for the study can be used to inform the design and implementation of future iterations of FUMES.

3.2 Research Methodology

Aspects of action research were adopted during this study, as while it was primarily concerned with advancing understanding of the design of 3D, problem-based learning environments, it also

addressed a genuine real world training requirement for mining personnel at the Challenger mine. Action-based research seeks to contribute to the practical concerns of people in an immediate problematic situation by developing their understanding and facilitating their critical reflection in order to be able to resolve problems that confront them (Banfield & Cayago-Gicain, 2006; Rapoport, 1970). In order to accomplish this, action-based research relies on collaboration between the researcher and practitioner to effect solutions to practical problems as a means of facilitating change and developing associated theory (Holter & Schwartz-Barcott, 1993). To this end, the research approach calls for the development of a 3D simulation environment (FUMES) with the purpose of providing an emergency evacuation training platform for personnel at the Challenger mine. The development of FUMES was informed by the SUPL Design Framework in association with subject matter experts at Challenger who were familiar with the real world problem scenario that was to be represented.

Elements of design-based research methodology were also used in the research approach as this methodology is concerned with designing learning environments and developing theories of learning (Dede et al., 2004). Design-based research utilises a design orientated focus and the assessment of critical design elements as a means of guiding educational refinement (Collins, Joseph, & Bielaczyc, 2004). Furthermore, it seeks to improve educational practices through iterative analysis, design, development, and implementation, based on collaboration among researchers and practitioners in real-world settings, leading to contextually-sensitive design principles and theories (Mott, McGowan, Seawright, & Allen, 2008). Consistent with action research, design-based research emphasises collaboration amongst researchers and practitioners that is anchored in practice with a commitment towards theory construction and explanation while solving real world problems (Mott et al., 2008; T. Reeves, Herrington, & Oliver, 2005; Yutdhana, 2005). As such, design-based research is well suited for assessing the efficacy of the SUPL Design Framework for developing 3D problem-based learning environments based on gaming technology. However, it should be noted that only one implementation cycle will be actualised during the study, with a view towards establishing design guidelines which can be used to inform subsequent iterations of FUMES.

A triangulated approach to data collection and analysis was implemented to differentiate between: (1) the factors that affected the outcome of training using FUMES as a result of the validity of the design that was derived using the SUPL Design Framework, and (2) the contextual factors that related to its development, including the technical factors inherent in its construction, the nature of the problem-solving scenario at Challenger, and the context in which

learning occurred. In this manner, the data that was collected via participant experience with FUMES could be used to answer the research questions proposed by this study. A deep and constant comparative approach to analysis was necessary due to the embedded nature of the study, whereby multiple sources of data relating to participant experience within FUMES could be triangulated in order to identify generalisable findings which were relevant beyond the immediate context of the study.

Addressing the first research question entailed determining how successfully FUMES could function as a training platform by measuring its ability to transfer knowledge in addition to evaluating the components of the SUPL Design Framework that contributed to this end. Given that the underground mine at Challenger was not suitable for operational training or performance testing in this regard as it was operational twenty four hours a day, measures of transfer were employed that did not require any participant presence in the underground mine itself.

Addressing the second research question required identifying the extent to which the collection of design factors constituting the SUPL Design Framework supported problem-based learning and the transfer of problem-solving knowledge. This entailed identifying whether the design factors could be determined as having had a bearing on the performance of participants within FUMES by virtue of the evaluation criteria established in Chapter 2.4.

3.3 Research Methods

The research approach for this study involved the collection and interpretation of both quantitative and qualitative data. Quantitative data provides a numerical representation of observations for the purpose of describing and explaining the phenomena that those observations reflect, while qualitative data provides for non-numerical examination and interpretation of observations for the purpose of discovering underlying meanings and patterns of relationships (Babbie, 1983, p. 537). The primary distinction between qualitative and quantitative approaches to research can be identified according to the different methods by which each defines problems, and in turn, searches for answers:

> Qualitative methods lend themselves to discovering meanings and patterns
> while quantitative methods seek causes and relationships demonstrated

statistically, a theoretical perspective, positivism, that is concerned with facts, prediction, and causation and the the subjective nature of the groups or individuals of interest. Researchers in the qualitative mode seek understanding through inductive analysis, moving from specific observation to the general. Quantitative analysis, on the other hand, employs deductive logic, moving from the general to the specific, i.e., from theory to experience (Bloland, 1992, p. on–line).

Based on this distinction, it would at first appear that qualitative and quantitative approaches to research are diametrically opposed. However, adopting a convergent, or triangulating methodology, which utilises both approaches, can be beneficial (Jick, 1979). Triangulation is possible because, if methods are systematically understood and rigorously used, points of connection can be identified such that both types of methods are addressing the same phenomenon (Fielding & Schreier, 2001). A convergent methodology exists as a vehicle for cross validation when two or more distinct methods that are used to examine the same dimension of a research problem are found to yield comparable data (Jick, 1979).

As such, two groups consisting of employees at the Challenger mine site were used during the study to evaluate FUMES and the SUPL Design Framework in terms of the criteria derived in Chapter 2.5. One group was comprised of employees with at least 6 months of full time experience at Challenger (Experienced Participants), while the second group consisted of employees who were new or had only recently arrived at the mine (Novice Participants). The 41 participants used in the study were selected by Dominion, comprising 21 Experienced Participants and 20 Novice Participants respectively. They were considered to have a common minimum level of understanding of the Challenger mine and its emergency evacuation procedures as a result of induction training. Differing perspectives between the participant groups were utilised to determine the degree of learning transfer and quantify the extent to which the design factors identified in the SUPL Design Framework supported this process.

All participants were provided with an introductory letter (Appendix 1) which explained the purpose of the research, and a reference sheet (Appendix 3) detailing the control scheme and interface utilised by FUMES. Novice Participants were also provided with a Mine Layout Diagram which detailed the general layout of the mine in addition to locations of refuge chambers and escape rises (see Appendix 4). A dedicated desktop computer was provided for FUMES on-site at Challenger for participants to use, comprising an Intel Core i7 950 3.06GHz

CPU, 4GB DDR3 RAM, an eVGA GTX260 896 MB dedicated 3D graphics card, and a 23" HD LCD monitor.

Participants using FUMES were required to complete a series of three problem-solving instances which were situated within the context of an underground fire emergency evacuation scenario at Challenger. These problem-solving instances were designed to develop appropriate knowledge and skills that could be transferred and utilised in similar scenarios in the real world mine.

FUMES presented participants with an initial briefing, explaining the objective, control scheme, feedback mechanisms, assessment measures, and key concepts, followed by the series of problem-solving instances which required participants to evacuate to a refuge chamber under increasingly severe environmental conditions. Given Novice Participants' lack of experience within the Challenger mining environment, the Training Staff Member responsible for administering participants through FUMES was instructed to assist hopelessly lost participants orientate themselves in the event that their efforts to reach a refuge chamber were significantly misdirected. At the conclusion of each problem-solving instance, participants were presented with an overview of their performance followed by a series of question prompts which were designed to promote reflective thinking based on their experience.

In order to facilitate a convergent research methodology, both qualitative and quantitative data collection methods were utilised so that a constant comparative approach to data analysis was possible. Data collection consisted of a variety of measures designed to measure the degree of learning transfer and extent to which the design considerations identified by the SUPL Design Framework facilitated this process, consisting of:

- Web-based questionnaires for all Experienced Participants and Novice Participants (QU_EP and QU_NP), which were utilised immediately following participant interaction with FUMES in order to elicit information pertaining to their experience (Appendix 5 and 6). These questionnaires were predominately composed of Likert scale (questionnaire) measures (strongly disagree, disagree, neutral, agree, strongly agree);
- Detailed phone interviews with 4 Experienced Participants and 3 Novice Participants (INT_EP and INT_NP), which were designed to provide in-depth accounts of participant experience with FUMES (Appendix 7 and 8);
- A detailed phone interview with the Training Staff Member at Dominion who was

responsible for processing participants through FUMES (INT_SM), which was designed to provide an additional perspective on participant performance (Appendix 9);

- Input logs, consisting of time stamped keystroke and mouse movements detailing the nature of participant interaction, such that an exact record of all participant input could be preserved and replayed through FUMES for later analysis (LOG_EP and LOG_NP), and;

- Database entries for all participants (PERF_EP and PERF_NP), which recorded how effectively they performed during each problem-solving instance. The measures recorded by FUMES are detailed in Table 3.1.

Table 3.1. Participant performance measures recorded for each problem-solving instance

Performance measure	Details
Outcome	The result of a given problem-solving instance (successfully reaching a refuge chamber, failure due to exposure to fire, or failure due to exposure to smoke)
Time taken	The time taken for the outcome of a given problem-solving instance to be decided
Distance travelled	The distance travelled through the virtual mine before the outcome of a given problem-solving instance was decided
Self-rescuer duration	The duration of time for which the self-rescuer was equipped before the outcome of a given problem-solving instance was decided
Remaining self-rescuer capacity	The remaining capacity of the self-rescuer (expressed as a percentage) at the point at which that outcome of a given problem-solving instance was decided
Total exertion	The total exertion value for a given problem-solving instance, the value of which is incremented per second in accordance with Table 76
Selected refuge chamber	Denotes whether or not the ideal refuge chamber was reached for a given problem-solving instance
Route to refuge chamber	Denotes whether or not the ideal route to refuge chamber was taken for a given problem-solving instance

3.3.1 Research Question 1

Answering the first research question measured learning transfer using methods that did not require performance testing of participants in the Challenger mine. Methods for measuring transfer (Lathan, Tracey, Sebrechts, Clawson, & Higgins, 2002) were derived in Table 3.2 as follows:

Table 3.2. Methods for measuring transfer from the 3D simulation environment

Method	Description	Remarks	Participants
Operator opinion	Operators, instructors, training specialists and students are asked to give their opinions on the perceived training value of a simulator, features of the simulators, or probable impact of simulator based training on subsequent real world performance.	Useful when operational training or performance testing is not feasible. However, assumes the operator, instructor, or trainee is able to assess objectively how much is learned from the simulator. May fail to recognise that such opinion is based on previous knowledge and experience.	Experienced Participants Novice Participants Training Staff Member
Assessment of fidelity	Describes the physical similarity between the simulator and the real-world environment, equipment, interface, or facility.	This method assumes that higher fidelity will yield higher transfer. Training may be possible with far less sophisticated devices. In addition, it appears that high fidelity generates user acceptance, but this itself does not mean that a device is more effective at training operators.	Experienced Participants
Inverse transfer of training	Experts at the operational task perform the same tasks, without practice, in a simulator. A positive result assumes that a suitable training program exists for the simulator.	The experienced operator is already proficient at the task and may have highly generalised skill. The simulator may be suitably designed for the evocation of a particular set of behaviours from a skilled operator.	Experienced Participants Novice Participants Training Staff Member

The required data and data collection tools for measuring transfer using the methods detailed in Table 3.2 are listed in Table 3.3 accordingly:

Table 3.3. Required data and collection tools for measuring learning transfer

Method	Required data	Data collection tools
Operator opinion	Likert scale (questionnaire)	• QU_EP(28.2, 28.3, 28.4, 29.1) • QU_NP(27.2, 27.3, 27.4, 28.1)
	Detailed description (interview)	• INT_EP(3) • INT_NP (3) • INT_SM (6)
Assessment of fidelity	Likert scale (questionnaire)	• QU_EP(29.2, 29.3)
	Detailed description (interview)	• INT_EP(4, 11, 12)
Inverse transfer of training	User performance (performance measures)	• PERF_EP • PERF_NP
	Observable actions within simulation environment (input logs)	• LOG_EP • LOG_NP
	Detailed description (interview)	• INT_SM (7, 8, 9, 10)

* Numbers in brackets denote corresponding questionnaire or interview question numbers

3.3.2 Research Question 2

Addressing the second research question entailed validating the design considerations identified by the SUPL Design Framework and analysing the data collected during the FUMES implementation to identify guidelines that supported knowledge construction and transfer in 3D problem-based learning environments. The required data and collection methods for evaluating the impact of these design factors are detailed in Tables 3.4, 3.5, and 3.6 for Situational Analytical Factors, Situational Design Considerations, and Problem-based Learning Design Principles, respectively. These design considerations were explored with respect to the user, the problem-solving task, and the 3D simulation environment.

Table 3.4 Required data and collection methods for situation analytical factors

Factor	Criteria for evaluation	Required data	Data collection tools
Prior knowledge	Previous experience with contextually similar problems	Likert scale (questionnaire)	• QU_EP (2.1, 2.2) • QU_NP (2.1, 2.2)
		Detailed description (interview)	• INT_EP (19) • INT_NP (18)
	Identification of unknown entities in the problem	Detailed description (interview)	• INT_EP (20) • INT_NP (19) • INT_SM(8, 9)
	Evidence of learning transfer		• See Table 24
Domain knowledge	Identification of objects, events, and ideas relevant to the problem	Detailed description (interview)	• INT_EP (21) • INT_NP (20)
	Identification of information necessary for resolving the problem	Detailed description (interview)	• INT_EP (22) • INT_NP (21)
Structural knowledge	Identification of relationships in the problem domain	Detailed description (interview)	• INT_EP (23, 24, 25, 26) • INT_NP (22, 23, 24, 25)
General problem-solving skills	Reliance on general problem-solving skills	Likert scale (questionnaire)	• QU_EP (2.3, 2.4) • QU_NP (2.3, 2.4)
		Detailed description (interview)	• INT_EP (27) • INT_NP (26)
	Specificity of the problem-solving strategy	Detailed description (interview)	• INT_EP (28) • INT_NP (27) • INT_SM (8)
Situatedness	Situatedness relative to the real world problem	Likert scale (questionnaire)	• QU_EP (3.1, 3.2, 3.3, 3.4)
Three	Three-dimensional	Likert scale	• QU_EP (13.2,

dimensional representation	representation of the environment	(questionnaire)		13.3, 13.4)
			·	QU_NP (12.2, 12.3, 12.4)
	Extent to which knowledge is effectively communicated	Likert scale (questionnaire)	·	QU_EP (14.1, 14.2, 14.3, 14.4, 15.1, 15.2, 15.3)
			·	QU_NP (13.1, 13.2, 13.3, 13.4, 14.1, 14.2, 14.3)
		Detailed description (interview)	·	INT_EP (3, 14)
			·	INT_NP (3, 13)
Immediate system response	Perceived immediacy of system response to input	Likert scale (questionnaire)	·	QU_EP (18.2)
			·	QU_NP (17.2)
	Consistency of frame rate	Likert scale (questionnaire)	·	QU_EP (19.1)
			·	QU_NP (18.1)
		User performance (performance measures)	·	PERF_EP
			·	PERF_NP
	Perceived sense of presence	Likert scale (questionnaire)	·	QU_EP (18.1)
			·	QU_NP (17.1)
		Detailed description (interview)	·	INT_EP (17)
			·	INT_NP (16)
Authenticity of the simulation environment	Physical fidelity	Detailed description (interview)	·	INT_EP (11)
		Likert scale (questionnaire)	·	QU_EP (3.2, 29.2, 29.3, 8.2, 13.1)
			·	QU_NP (7.2, 12.1)
	Functional fidelity	Detailed description (interview)	·	INT_EP (12)
		Likert scale (questionnaire)	·	QU_EP (3.4, 8.5, 9.1, 9.2, 9.5, 15.1, 15.2, 17.4, 20.3, 20.4)
			·	QU_NP (7.5, 8.1, 8.2, 8.5, 14.1, 14.2, 14.4, 19.3, 19.4)
High visual fidelity	Quality of visual elements	Likert scale (questionnaire)	·	QU_EP (13.1, 16.1, 16.2, 16.3)
			·	QU_NP (12.1, 15.1, 15.2, 15.3)
	Richness of information content	Detailed description (interview)	·	INT_EP (15)
			·	INT_NP (14)
	Perceived sense of immersion	Likert scale	·	QU_EP (17.3,

		(questionnaire)	11.3) · QU_NP (16.3, 10.3)
		Detailed description (interview)	· INT_EP (16) · INT_NP (15)
	Perceived sense of presence	Likert scale (questionnaire)	· QU_EP (18.1) · QU_NP (17.1)
		Detailed description (interview)	· INT_EP (17) · INT_NP (16)

* Numbers in brackets denote corresponding questionnaire or interview question numbers

Table 3.5. Required data and collection methods for situation design considerations

Factor	Criteria for evaluation	Required data	Data collection tools
Structuredness	Extent of existing domain specific knowledge and general problem-solving skills	Detailed description (interview)	· INT_EP (30, 31)
		Likert scale (questionnaire)	· QU_EP (5.1, 5.2, 5.3, 6.1, 6.2, 6.3, 6.4, 7.1, 7.2, 7.3) · QU_NP (4.1, 4.2, 4.3, 5.1, 5.2, 5.3, 5.4, 6.1, 6.2, 6.3)
	Perceived familiarity of the problem	Likert scale (questionnaire)	· QU_EP (3.5, 4.1, 4.2) · QU_NP (3.1, 3.2, 3.3)
		Detailed description (interview)	· INT_EP (29, 32) · INT_NP (28, 31)
Complexity	Perceived uncertainty of the problem-solving context	Likert scale (questionnaire)	· QU_EP (8.2, 8.3) · QU_NP (7.2, 7.3)
		Detailed description (interview)	· INT_EP (33, 34) · INT_NP (32, 33)
	Perception of related entities within the problem domain	Detailed description (interview)	· INT_EP (35) · INT_NP (34)
	Recognition of problem complexity	Likert scale (questionnaire)	· QU_EP (10.1, 10.2, 10.3) · QU_NP (9.1, 9.2, 9.3)
		Detailed description (interview)	· INT_EP (28) · INT_NP (27)
Domain specificity	Perceived meaningfulness of the problem	Likert scale (questionnaire)	· QU_EP (8.4, 10.4, 10.5) · QU_NP (7.4, 9.4, 9.5)
		Detailed description (interview)	· INT_EP (36) · INT_NP (35)
	Problem-solving strategies	Detailed description	· INT_EP (28)

	employed	(interview)	· INT_NP (27) · INT_SM (8)
	Extent to which problem is contextualised		
		Detailed description (interview)	· INT_EP (39, 40, 41) · INT_NP (38, 39, 40)
Authenticity of information	Consistency of information	Detailed description (interview)	· INT_EP (57, 58)
Problem representation	Perception of the problem representation	Detailed description (interview)	· INT_EP (42, 61) · INT_NP (40, 54)
	Identification of relevant problem features	Detailed description (interview)	· INT_EP (21) · INT_NP (20)
	Identification of relationships	Detailed description (interview)	· INT_EP (23, 24, 25, 26) · INT_NP (22, 23, 24, 25)
	Problem-solving strategies employed	Detailed description (interview)	· INT_EP (28) · INT_NP (27) · INT_SM (8)
User control	Support for movement and interaction	Likert scale (questionnaire)	· QU_EP (20.1, 20.2) · QU_NP (19.1, 19.2)
		Detailed description (interview)	· INT_EP (18) · INT_NP (17)
	Perceived sense of presence	Likert scale (questionnaire)	· QU_EP (18.1) · QU_NP (17.1)
		Detailed description (interview)	· INT_EP (17) · INT_NP (16)
	Quality of collision detection	Likert scale (questionnaire)	· QU_EP (20.3, 20.4) · QU_NP (19.3, 19.4)
		Likert scale (questionnaire)	· QU_EP (20.3, 20.4) · QU_NP (19.3, 19.4)

* Numbers in brackets denote corresponding questionnaire or interview question numbers

Table 3.6. Required data and collection methods for Problem-based Learning Design Principles

Factor	Criteria for evaluation	Required data	Data collection tools
Feedback	Perception and understanding of feedback	Detailed description (interview)	· INT_EP (43) · INT_NP (41)
		Likert scale (questionnaire)	· QU_EP (24.5, 25.1, 25.2, 25.3)

			· QU_NP (23.5, 24.1, 24.2, 24.3)
	Modification of user behaviour due to feedback	Observable actions within simulation environment (input logs)	· LOG_EP · LOG_NP
	Relevance of feedback	Likert scale (questionnaire)	· QU_EP (25.4, 25.5) · QU_NP (24.4, 24.5)
		Detailed description (interview)	· INT_EP (44, 45)
	Integration of feedback	Detailed description (interview)	· INT_EP (6) · INT_NP (5)
Assessment	Validity of assessment	Detailed description (interview)	· INT_EP (46) · INT_SM (10)
	Fidelity of assessment	Detailed description (interview)	· INT_EP (48)
	Integration of assessment	Detailed description (interview)	· INT_EP (7) · INT_NP (6)
Information	Extent of information available	Detailed description (interview)	· INT_EP (51, 52) · INT_NP (46, 47)
		Likert scale (questionnaire)	· QU_EP (22.2) · QU_NP (21.2)
	Integration of information	Detailed description (interview)	· INT_EP (9) · INT_NP (8)
	Application of information	Detailed description (interview)	· INT_SM (20)
Learner control	Control of the learning process	Detailed description (interview)	· INT_EP (49) · INT_NP (44)
		Likert scale (questionnaire)	· QU_EP (21.2, 21.3) · QU_NP (20.2, 20.3)
	Integration of learner control	Detailed description (interview)	· INT_EP(8) · INT_NP(7)
	Suitability of learner control	Detailed description (interview)	· INT_EP (A0) · INT_NP (19) · INT_SM(8, 9)
Reflection	Identification and development of new knowledge	Detailed description (interview)	· INT_EP (54, 55) · INT_NP (49, 50)
	Future applications of new knowledge	Detailed description (interview)	· INT_EP (56) · INT_NP (51)
	Integration of reflection	Likert scale (questionnaire)	· QU_EP (24.1, 24.2, 24.3, 24.4)

		•	QU_NP(23.1, 23.2, 23.3, 23.4)
	Detailed description (interview)	• •	INT_EP(10) INT_NP(9)

* Numbers in brackets denote corresponding questionnaire or interview question numbers

3.4 Summary for Methodology

The methodological approach to this study is grounded in action research and design-based research and calls for the implementation of a 3D simulation environment within an underground mining context for the purpose of developing knowledge for real world application. FUMES was developed for this purpose to address the emergency evacuation training needs of the Challenger underground gold mine located in South Australia.

In order to determine the efficacy of FUMES and the SUPL Design Framework, participants were drawn from amongst personnel at the Challenger and tasked with evacuating from a simulated representation of the mining environment. Evaluation criteria established from the literature was used for this purpose in accordance with questionnaire, interview, and performance data collected from forty-two participants who were comprised of personnel working at Challenger. The process by which FUMES was designed to meet the training requirements of the Challenger mine in accordance with the SUPL Design Framework is documented in detail in the next chapter.

4 Designing the 3D Simulation Environment

This study required the design and development of a 3D simulation environment as a means of exploring learning transfer and validating the effectiveness of the SUPL Design Framework. The Fires in Underground Mines Evacuation Simulator (FUMES) was developed to address safety and training requirements necessitating the development of knowledge and skills for emergency evacuation at the Challenger underground mining facility.

The SUPL Design Framework was derived from a review of the literature which explored problem-based learning, learning transfer with computer simulations, and 3D environments (Chapter 2). A series of key design considerations directed towards the transfer of knowledge to real world problem-solving scenarios were elicited in this manner as detailed in Figure 4.1:

User

Prior knowledge

Domain knowledge

Structural knowledge

General problem-solving skills

Structuredness

Complexity

Domain specificity

Feedback

Assessment

Information

Learner control

Reflection

User control

High visual fidelity

Authenticty of the simulation environment

Immediate system response

Situatedness

Problem representation

Authenticity of information

3D Representation

Problem-solving Task

3D Simulation Environment

Situational Analytical Factors

Situational Design Considerations

Problem-based Learning Design Principles

Figure 4.1. FUMES was designed using the SUPL Design Framework

As summarised in Chapter 2.5, design considerations in the the SUPL Design Framework were organised in accordance with their relation to the user, the problem-solving task, and the 3D simulation environment. Design considerations that were relevant to only one of these three components were designated Situational Analytical Factors, with those that related to two or all three components defined as Situational Design Considerations and Problem-based Learning Design Principles, respectively.

This chapter details the design of FUMES in accordance with the SUPL Design Framework. This process comprises an initial situational analysis of the context of learning in which emergency evacuation scenarios are situated at Challenger via consultation with Subject Matter Experts, including the establishment of learning objectives (Chapter 4.1). This information was subsequently used to characterise the Situational Analytical Factors (Chapter 4.2), which in turn inform the delineation of Situational Design Considerations (Chapter 4.3), and Problem-based Learning Design Principles (Chapter 4.4) for the simulation.

4.1 Context for Learning

Dominion Mining requested a computer-generated simulation of their Challenger gold mine to be utilised as part of their emergency training procedures for underground fire scenarios. These scenarios are highly dangerous due to the confined nature of the underground mining environment and mining personnel need to be made aware of correct evacuation procedures in order to minimise the risk of harm during an emergency.

Underground fires at Challenger are often caused by excess heat from brake or differential issues in mining vehicles. These fires can produce a significant amount of smoke which can quickly overwhelm personnel due to the confined nature of the underground mining environment. Furthermore, this smoke can also reduce visibility to near nothing in the space of ten to twenty minutes depending on the location of the fire and the ventilation in the mine at the time. Once fire or smoke has been observed, an evacuation is ordered over the emergency radio channel and the stench gas system is activated, flooding the mine with a colourless gas with a very distinct odour similar to 'rotten onions' in order to signify this event. The individual who initiates the emergency announcement over the radio will identify the location at which smoke or fire has been reported, followed by ordering all personnel to evacuate. After this, the individual will switch the radio to emergency mode, which triggers all vehicle radios to play a pre-recorded emergency message on loop.

Dominion's existing emergency evacuation procedures direct personnel to retreat to one of several refuge chambers in the event of a fire located at incremental depths throughout the mine, as listed in Table 4.1.

Table 4.1. Location of refuge chambers in the Challenger mine

Depth level	Type of refuge chamber
1020 Level	6 person refuge chamber
940 Level	6 person refuge chamber
860 Level	12 person refuge chamber
800 Level	12 person refuge chamber
740 Level	12 person refuge chamber

These refuge chambers, as depicted in Figures 4.2 and 4.3, provide a safe haven for personnel while they await rescue and are self contained, with their own battery power supply and oxygen cylinders independent to the power and air that is provided from the surface. Refuge chambers are outfitted with flashing lights to indicate their status in this regard, with green and red lights indicating the use of external or internal supplies of oxygen and power respectively. These lights also act as navigational aides and are designed to pierce through smoke or dust in order to increase visibility.

Figure 4.2. Minearc refuge chamber. Image sourced from
http://www.minearc.com/docs/MineARC_Chambers.pdf

Figure 4.3. Twelve person refuge chamber in the Challenger mine

The method advocated by Dominion for reaching a refuge chamber in the event of an emergency evacuation underground is specified in detail during induction training for personnel at the Challenger mine. In the event that personnel become aware that an emergency evacuation has been declared they are instructed to:

- Park up any vehicles they may be travelling in off the primary mine shaft, angled into the wall, with the engine turned off;
- Evacuate immediately to the nearest refuge chamber to the area in which they are working, walking down the primary mine shaft if possible. Personnel should not attempt to walk past or extinguish the fire unless it is small and they are confident to do so;
- Notify other personnel on the way if they are not aware of the emergency evacuation, and;
- Utilise a self rescuer if smoke is encountered along the way to the nearest refuge chamber.

Chapter 4   Designing the 3D Simulation Environment

Subject Matter Experts at Challenger identified a series of environmental conditions which could impact the ability to evacuate to refuge. These environmental conditions formed a basis for the identification of the problem through the SUPL Design Framework and are listed in Table 4.2 as follows:

Table 4.2. Environmental conditions which may affect the ability to evacuate

Hazard	Description	Effect
Fire	Vehicle fire underground	· Likely to cause death or serious injury if too close · Obstruction to movement · Restricts access to parts of the mining environment · Can result in failure of external power supply
Smoke	Smoke generated from vehicle fire	· Will cause death if no source of breathable oxygen is available · Reduction in visibility · Requires movement to be restricted to distances that can be covered by the limits of the self rescuer
External power failure	Power supply from the surface is interrupted	· Fixed lighting sources within the mine no longer function · Refuge chambers switch to internal power supplies
External oxygen supply failure	Oxygen supply from the surface is interrupted	· Oxygen supply from the surface is interrupted · Refuge chambers switch to internal oxygen supplies
Lighting conditions	Low lighting conditions owing to insufficient proximity to lighting sources, or interruption in external power supply, which renders fixed lighting sources within the mine inoperable	· Restricts effective movement and navigation · May reduce awareness of other environmental hazards · Greater reliance on cap lamp to assist movement and navigation

Dominion employees who enter the underground mine at Challenger are outfitted with standard equipment including a belt, a helmet, safety glasses, and a cap lamp, which is a light attached to the helmet. The cap lamp has high beam and low beam settings, the duration of which lasts according to a portable battery affixed to the miner's belt which provides fifteen to thirty hours of light respectively, and can be effective up to distances of fifty metres. All personnel are also outfitted with a personal radio if not working with a mining vehicle, and a self rescuer, which is a portable gas mask which provides oxygen for use when there is a lack of breathable air within the mining environment. The self rescuer is attached to the miner's belt inside a metal case, which is then opened during an emergency to deploy the oxygen bag and breathing apparatus,

the process of which takes approximately thirty seconds. The duration of the oxygen supply provided by a self rescuer is contingent on the level of physical activity of the person who is wearing it as approximated in Table 4.3.

Table 4.3. Duration of oxygen supply provided by a self rescuer as a product of physical activity

Level of Physical Activity	Example Activity	Duration of Oxygen Supply
Low	Stationary	~ 100 minutes
Medium	Walking	~ 30 minutes
High	Running or climbing an escape rise ladder	~ 10 minutes

All personnel at Challenger are provided with induction training at the commencement of employment which informs them as to the characteristics of the Challenger mining environment and the key safety concerns in the event that an emergency evacuation is required. Instructional videos, power-point presentations, and practical demonstrations are used during induction training to provide the following information:

- Identifying and demonstrating safety systems, all personal protective equipment, plans of the mine, mining techniques, mining equipment, and people at work within the mine;
- Informing new personnel as to the hazard of underground fires (Table 4.2) and the manner in which an emergency evacuation is declared if one is detected within the mining environment;
- Demonstrating the location and function of escape rises and refuge chambers to new personnel, and;
- Requiring new personnel to traverse between levels of the mine using both the main decline and escape rises to reach a refuge chamber in order to demonstrate what may be required in the event of an emergency.

4.1.1 The Challenger Mining Environment

The Challenger mine itself consists of a 5.5 metre square primary shaft, referred to as the decline, that descends parallel to the main ore body with additional smaller protruding shafts to facilitate ore extraction. The decline is arranged in a spiral like configuration which descends in

twenty metre vertical increments, or one hundred and forty metres on a 1:7 decline, between subsequent levels of the mine. Each level has a vent rise, for controlling air flow within the mine, and an escape rise, which is a ladder that allows personnel to climb the twenty metre vertical distance between levels of the mine rapidly in the event that access to, or usage of, the main decline is obstructed during an emergency. Personnel are instructed during induction training to not use escape rises during a fire under any circumstances except where there is a blockage to the decline which needs to be cleared in order to reach a refuge chamber. Figure 4.4 details the general layout and structure of the Challenger mine with the locations of vent rises, escape rises, and refuge chambers marked accordingly.

Figure 4.4. Side elevation of Challenger mine

Chapters of the Challenger mine are identified and labelled according to their depth below the main portal, which is the primary entry and exit point underground. The depth of each level of the mine is marked on the walls in locations where smaller shafts branch off from the decline, with the location of escape rise ladders marked in a similar fashion with reflective green signage to indicate their direction. Figure 4.5 displays a Chapter of the Challenger mine where a sub-shaft leaves the main decline with visible depth marking and escape rise signs.

Figure 4.5. Examples of depth level and reflective green escape rise signs within the Challenger mine

The Challenger mining environment consists predominantly of large expanses of uniform and largely featureless gneiss rock surfaces which offer little in the way of identifiable features that may be used to aid navigation and way-finding. As a result, the few visual cues that are present within the mining environment are especially important due to their contrast in comparison to the rest of the environment. This is especially the case with regards to the depth markings, reflective signage that is used to indicate the direction of escape rises from the decline, and the flashing lights on refuge chambers.

The depth markings that are painted onto the rock surface along the walls of the decline provide valuable information regarding the exact depth level of the mine that an individual is currently on and where the current level is in relation to those above and below it. These depth markings can provide valuable spatial information regarding the number of levels that are required to be traversed in order to reach a refuge chamber, as Dominion employees are informed as to the specific levels on which refuge chambers are located (see Table 4.1) during induction training.

The reflective green escape rise signage is also a significant aid to spatial navigation due to the reflective properties of the material on which the sign is printed. When struck with a light source such as a miner's cap lamp, these signs become incandescent and easily identifiable in contrast to the rock wall to which they are attached. These visual cues serve to indicate the direction of escape rises and refuge chambers from the decline when close enough to be read, but also serve as a directional aid from a much further distance owing to their reflective properties.

The flashing lights on the refuge chambers themselves also provide very clear spatial indicators as to their proximity and direction. The lights are prevalent spatial cues in circumstances where visibility is constrained due to the presence of smoke or dust within the mining environment. Under these circumstances, the piercing nature of the light is more capable of penetrating the smoke or dust than a standard light source and thus acts as a beacon to assist in locating and reaching the chamber. Additionally, these lights also provide further pertinent information regarding the status of the external oxygen and electrical supplies to the refuge chamber. A green flashing light is used to indicate normal supply, while a red flashing light is used to indicate that the supply has been compromised.

In addition to depth markings and reflective signage, a number of other visual cues exist within the mining environment which contrast the uniformity of the rock wall surface. Jumbo boxes, which are electrical boxes which provide a power source for work within the mine, and cabling and overhead piping for controlling air flow are also scattered throughout the mining environment. Whilst these objects do not provide the same degree of spatial information as the depth markings and reflective signage, their presence can provide some assistance to navigation and way-finding, particularly to individuals who are sufficiently familiar with the Challenger mining environment. The visual cues used to navigate the mining environment established from information provided by Subject Matter Experts at Challenger are detailed in Table 4.4 accordingly:

Table 4.4. Visual cues used to navigate within the mining environment

Visual cue	Description	Significance
Depth markings	White, rectangular markings with a red border and red font which indicate the current depth level as painted on the wall of the decline	• Provide a clear indication as to current depth level within the mine • Can be used to determine the number of levels required to be traversed in order to reach a refuge chamber
Reflective signage	Green, reflective sign indicating the direction of escape rises from the decline	• Information displayed on the sign indicates the direction of an escape rise from decline • Reflective properties of the sign enables it to be noticeable from a great distance when struck by a beam of light
Refuge chamber lights	Flashing light which is green or red depending on the status of air and power supply to the refuge chamber which is designed to pierce through smoke or dust	• Only of aid when in close proximity to the refuge chamber • Of more significance when visibility is poor, especially where smoke or dust is present
Jumbo boxes	Electrical power source	• Have a fluorescent light attached them, which is the only source of fixed lighting within the mine
Assorted infrastructure	Service cabling and piping, vent bags, and other infrastructure used to support mining operations	• Can serve as navigational aides, particularly to individuals who are familiar with the mining environment

Given the underground location of the mine, the absence of natural light sources result in an environment that is very dark and difficult to see in without the use of artificial sources of light. To alleviate this, fluorescent lights are attached atop of the jumbo boxes within the mine at Challenger. However, these jumbo boxes are situated only where electrical power is required, thus Dominion employees must rely on the light from their mining vehicles, in addition to that provided by their cap lamp in order to see effectively. The cap lamp light provides a focussed beam which only illuminates a small area at a time, and provides far less light in comparison to mining vehicles or jumbo box lights. However, when not in close proximity to vehicle or jumbo box lights, or during situations where external power to the mine is lost, cap lamps provide the only source of light for Dominion employees within the Challenger mine.

4.1.2 Learning Objectives

Learning aims and outcomes form the basis of design and need to be established at the onset of the design process (McMahon, 2009). To this end, the learning objectives for FUMES were received from the learning outcomes of the induction training used at Challenger. These were identified via consultation with Subject Matter Experts and are detailed in Table 4.5 as follows:

Table 4.5. Learning objectives for FUMES

Learning objective	Relevant knowledge	Relevant skills
Recognition of an emergency evacuation scenario	An emergency evacuation may be signalled via radio communication or by the release of stench gas	
Awareness of the primary goal during an emergency evacuation scenario	The primary objective for any personnel working within the mine once an emergency evacuation has been declared is to retreat to the nearest refuge chamber as quickly and safely as possible	
Awareness of the locations of refuge chambers within the mine	Refuge chambers are located on levels 1020, 940, 860, 800, and 740 within the Challenger mine. The flashing lights mounted on refuge chambers indicate their presence when in close proximity	
Awareness of the locations of escape rises within the mine	Escape rises are located in the sub-shafts on every level of the Challenger mine with their direction indicated via reflective green signs	
Understanding the layout and structure of the mine	Each level of the mine is separated by distances of 20 metres vertically, or 140 metres on a 1:7 decline. Each level of the mine is labelled according to its vertical distance from the main portal starting at 1200 and descending in intervals of 20 metres	
Performance of the emergency evacuation procedure	Park up all vehicles, go to the nearest refuge chamber, and utilise self rescuers if required. Personnel should also not attempt to walk past or extinguish the fire unless it is small and they are confident to do so.	Identifying the ideal refuge chamber Navigating to a refuge chamber safely and efficiently Utilising a self rescuer effectively
Application of visual cues that can assist navigation	Depth markings, reflective signage, refuge chamber lights, and other assorted infrastructure	Navigating to a refuge chamber safely and efficiently
Application of escape rises	Escape rises provide access between levels of the mine and are intended to only be used when the	Navigating to a refuge chamber

	decline is blocked in the event of a fire	safely and efficiently
Application of the self rescuer	Self contained personal oxygen supply for use in situations where the level of breathable air in the surrounding environment is not sufficient. Provides 100 minutes of oxygen at low physical exertion, 30 minutes at medium physical exertion, and 10 minutes at high physical exertion	Utilising a self rescuer effectively
Awareness of the function and capabilities of the cap lamp	Directional light attached to the miner's helmet which provides 30 hours of light at low beam setting, and 15 hours at high beam setting	
Awareness of the environmental conditions that can affect the ability to reach a refuge chamber	Fire, smoke, external power failure, external oxygen supply failure, insufficient oxygen in the mining environment, and lighting conditions in the mining environment	Navigating to a refuge chamber safely and efficiently

Having established the context of learning for emergency evacuations of the Challenger mine and established learning objectives based on those specified for mining personnel during induction training, it is now possible to move onto the design of the simulation using the SUPL Design Framework. This process entails the characterisation of Situational Analytical Factors, followed by the subsequent delineation of Situational Design Considerations and Problem-based Learning Design Principles using this information.

4.2 Situational Analytical Factors

Situational Analytical Factors encompass factors which exist outside the control of the designer that need to be accommodated to facilitate knowledge construction and learning transfer within a 3D problem-based learning environment. (Chapter 2.5). Specifically, this entails establishing the extent of existing knowledge that learners possess which is contextually relevant to the real world problem (Chapters 4.2.1 through 4.2.4), determining how situated the real world problem is (Chapter 4.2.5), and identifying the key characteristics of the real world problem to simulate within the 3D environment (Chapters 4.2.6 through 4.2.9).

4.2.1 Prior Knowledge

Subject Matter Experts indicated that personnel acquired prior knowledge of emergency evacuation scenarios within the Challenger mining environment during induction training. The training programme consisted of a familiarisation component, whereby personnel were required

to demonstrate their ability to reach a refuge chamber using both the main decline and escape rises in order to develop an awareness of what may be required in the event of an emergency evacuation (Chapter 4.1). This served as a prior problem-solving example, where personnel were provided with a statement of the problem, and subsequent procedure for finding a refuge chamber in order to demonstrate how similar emergency evacuation scenarios might be resolved. The prior knowledge acquired by mining personnel during induction training which needed to be accommodated within FUMES is outlined in Table 4.6, accordingly:

Table 4.6. Prior knowledge to be accommodated by FUMES

Prior knowledge	Details
Traversal of the Challenger mining environment	Personnel know how to traverse between levels of the mine using both the main decline and escape rises to reach a refuge chamber. This knowledge was acquired via first hand experience during induction training in order to familiarise themselves with the actions required in the event of an emergency.

4.2.2 Domain Knowledge

Induction training provided mining personnel at Challenger with knowledge of the real world problem domain. Subject Matter Experts indicated that personnel were presented with instructional materials which detailed the characteristics of the Challenger mining environment, the hazards of underground fires, and the process by which to evacuate to safety (Chapter 4.1). The function and location of escape rises and refuge chambers were also demonstrated via training staff at Challenger who showed personnel how to use their cap-lamp and self-rescuer during an emergency. The domain knowledge obtained by mining personnel via induction training which needed to be accommodated within FUMES is thus detailed in Table 4.7 as follows:

Table 4.7. Domain knowledge to be accommodated by FUMES

Domain knowledge	Details
Emergency evacuation initiation	An emergency evacuation event is declared via vehicle radio, personal radio, stench gas system, or by other personnel within the mine, signalling all personnel to retreat to the nearest available refuge chamber (see Table 33)
Emergency evacuation procedure	Knowledge of the emergency evacuation procedure utilised at Challenger during an emergency evacuation. Personnel are made aware that they need to safely evacuate to a refuge chamber during an emergency.
Escape rises	Escape rises are vertical ladder spans that traverse the twenty metre

	distance between levels of the mine. Escape rises are located on all levels of the mine, with their direction from the decline denoted by reflective green signs. Escape rises are intended to be used if access to the decline is obstructed during an emergency, and not to be used during a fire unless no other routes to a refuge chamber are available. Traversing escape rises is a physically demanding activity.
Refuge chambers	Self contained titanium chambers with electrical and oxygen supplies which act as a safe haven for personnel in the event of an emergency underground. Refuge chambers are located at levels 1020, 940, 860, 800, and 740, and are easily noticeable as a result of their flashing lights.
Spatial characteristics of the Challenger mine	The layout and structure of the Challenger mining environment, including the location and function of refuge chambers and escape ladders. The mine itself consists of a 5.5 metre square main shaft that descends on 1:7 ratio over 140 metres, such that each level of the mine is separated by distances of 20 metres vertically. The main decline has smaller shafts that branch off from it which are used to extract ore from the ore body. Some of these smaller shafts also lead to refuge chambers and escape rises. Each level of the mine is labelled according to its distance below the main portal and can be reached either via the decline or escape rises (see Figure 11)
Visual cues	Visual cues which could assist way-finding and navigation within the mine, including depth markings, reflective signage, refuge chamber lights, jumbo boxes, and other assorted infrastructure (see Table 35)
Basic navigation	Basic understanding of navigation within the mining environment.
Environmental conditions	Environmental conditions that could inhibit the ability to evacuate to a refuge chamber, such as fire, smoke, external power failure, external oxygen supply failure, and poor visibility (see Table 32)
Cap lamp	The function and characteristics of the cap lamp, which consists of a light attached to the miner's helmet which is powered by a battery carried on the miner's belt. The cap lamp has high and low beam settings, which last for approximately 15 to 30 hours respectively. The cap lamp has a small focussed beam which is used by personnel underground as their primary method of illumination in the event that they are not working in close proximity to a mining vehicle.
Self-rescuer	The function and characteristics of the self-rescuer, which consists of an oxygen container, breathing tube, and mouth piece which creates oxygen via a chemical reaction inside the container when activated. Self rescuers are intended for use is situations where the amount of breathable oxygen available within the environment is insufficient. The duration of oxygen supply is affected by the user's level of physical activity, where by low, medium, and high levels of exertion equate to durations of approximately 100, 30, and 10 minutes respectively (see Table 31).

4.2.3 Structural Knowledge

The structural knowledge that personnel obtained during induction training was identified during consultation with Subject Matter Experts at Challenger. This included knowledge of

relationships between movement speed, terrain inclination, physical exertion, and self-rescuer oxygen consumption as acquired during the familiarisation component of induction training with training staff at Challenger (Chapter 4.1). Table 4.8 details the structural knowledge that needed to be accommodated by FUMES in this regard as identified by Subject Matter Experts at Challenger.

Table 4.8. Structural knowledge to be accommodated by FUMES

Structural knowledge	Details
Self rescuer depletion	• The supply of oxygen in a self rescuer is depleted over time at a rate which is proportional to the breathing rate of its user • Greater physical exertion requires a greater intake of oxygen
Cap lamp depletion	• The use of a cap lamp on high beam setting will deplete the battery at approximately twice the rate compared to low beam setting • The use of a cap lamp on high beam setting will produce more light compared to low beam setting
Physical effort required to traverse the Challenger mining environment	• Physical exertion is dependent on the inclination of the surface (uphill, downhill, or level, and up or down an escape rise) and movement speed (standing still, walking, or running).
External power and oxygen supplies	• Non-functional fixed lighting sources (fluorescent lights on jumbo boxes) within the mine can indicate that external supply has been interrupted • Non-functional air flow fans within the mine can indicate that external supply has been interrupted • Flashing red lights on refuge chambers can indicate that external supply has been interrupted
Environmental conditions	• Smoke is a likely indication of fire, although smoke cannot be relied upon to indicate the location of the fire given the manner in which it travels within the underground mining environment • Exposure to smoke or fire can result in injury or death • Loss of external power and oxygen supplies is highly likely during an underground fire scenario

4.2.4 General Problem-solving Skills

As existing induction training was not geared towards the development of problem-solving skills, the extent of general problem-solving skill acquired by personnel at Challenger could not be determined with any degree of accuracy. Nevertheless, general problem-solving skills are important to the problem-solving process and should be accommodated within problem-based learning environments via the elicitation of domain specific knowledge (Smith, 1988).

4.2.5 Situatedness

Information provided by Subject Matter Experts suggested that the real world problem was highly contextualised owing to the unique spatial characteristics of the mining environment and the specific emergency evacuation procedure practised at Challenger. During an underground fire emergency, personnel were required to locate and evacuate to a refuge chamber in the safest and most efficient way possible whilst minimising their exposure to environmental hazards within the mine. Table 4.9 details the situated characteristics of the real world problem to be accommodated by FUMES in this regard:

Table 4.9. Situated characteristics of the real world problem to be accommodated within FUMES

Characteristic	Description
Spatial characteristics of the Challenger mining environment	Scale, distances between levels (both vertically and along the decline), and dimensions of the main shaft need to be consistent with respect to the Challenger mining environment. Virtual mine also needs to accurately embody the visual cues used in the real world mine that are used for navigation.
Environmental conditions at Challenger	Smoke and fire must be readily recognisable by users, and the lighting conditions of the Challenger mining environment must be represented consistently
Emergency evacuation procedure used at Challenger	Personnel are required to proceed to the nearest available refuge chamber when an evacuation has been ordered, emphasising safety and efficiency in order to preserve their self-rescuer oxygen supply, which should be utilised if smoke is encountered. Escape rises should be avoided during a fire unless they are the only means of clearing an obstruction.

4.2.6 3D Representation

Diagrams of the mine were utilised in addition to descriptions provided by Subject Matter Experts to identify the three-dimensional characteristics of the Challenger mining environment. These were established in relation to real world problem resolution, whereby effective orientation and navigation was required in order to successfully locate and evacuate to a refuge chamber during an emergency. This indicated that the layout and structure of the Challenger mine, including escape rise and refuge chamber locations, and the visual cues used to aid navigation were the key three-dimensional characteristics of the real world problem environment that needed to be accommodated by FUMES, as detailed in Table 4.10:

Table 4.10. 3D characteristics of the Challenger mine to be accommodated by FUMES

Characteristic	Details
Layout and structure of the mine	· Location, direction, and angle of decline and all drives accurate relative to real world environment · 20 metres vertically between levels · Main decline 5m wide, 5m high · Main decline descends at a ratio of 1:7 over 140 metres between levels
Locations of refuge chambers within the mine	· Located in small shafts just off the main decline on levels 1020, 940, 860, 800, and 740
Locations of escape rises within the mine	· Located in the drives that branch off from the decline on every level of the mine
Visual cues that can assist navigation	· Depth markings, reflective signage, refuge chamber lights, jumbo boxes, and assorted infrastructure (Table 4.4) · Location of visual cues consistent with the real world environment · Detail of visual cues consistent with the real world environment

4.2.7 Immediate System Response

Subject Matter Experts were consulted to identify the user activity that FUMES needed to respond to immediately in order to reflect the nature of real world problem-solving activity. The user activity that was required to be accommodated by FUMES in this regard consisted of movement, orientation, climbing an escape rise, equipping the self-rescuer, and changing the beam setting on the cap lamp, as established in Table 4.11.

Table 4.11. User activity to be accommodated by FUMES with an immediate system response

User activity	Characteristics of response
Movement, including walking and running	Immediate response which indicates the speed at which the user is moving through the mining environment
Orientation	Immediate response which demonstrates a corresponding change in viewing perspective
Climbing an escape rise	Immediate response which indicates that the user is climbing the escape rise
Putting on a self-rescuer	Immediate response which indicates that the user is in the process of equipping their self-rescuer
Changing the beam setting on the cap lamp	Immediate response which indicates that the brightness of the cap lamp light has changed.

4.2.8 Authenticity of the Simulation Environment

Physical and functional characteristics impacting the resolution of the real world problem needed to be accommodated within FUMES in order to authentically represent emergency evacuation procedures within the Challenger mine and encourage the transfer of knowledge. These were identified using information provided by Subject Matter Experts at Challenger and are detailed in Tables 4.12 and 4.13, accordingly.

Table 4.12. Physical characteristics to be accommodated within FUMES for authentic simulation

Characteristic	Details
Challenger mining environment	The Challenger mine as represented by FUMES needs to embody consistent physical and spatial characteristics in three dimensions
Escape rises	Escape rises in FUMES need to look the same as their real world counterparts so that they can be readily recognised and utilised during an emergency evacuation scenario
Refuge chambers	Refuge chambers need to look the same as their real world counterparts so that they can be readily recognised as they represent the goal of the real world problem
Visual cues	Visual cues within the Challenger mine need to be located in the same positions within FUMES so that they can be utilised to aid navigation and way-finding. The visual cues should also clearly resemble their real world counterparts so that they can be recognised and utilised easily.
Environmental conditions	Smoke and fire should be readily recognisable within FUMES so that they can be avoided. Smoke should also act as an impediment to visibility within FUMES.

Table 4.13. Functional characteristics to be accommodated within FUMES for authentic simulation

Characteristic	Details
Inclination of the terrain	Moving over inclined terrain requires requires greater physical exertion than moving over level or declined terrain.
Movement speed	Running requires greater physical exertion than walking. Remaining stationary requires less physical exertion than walking.
Physical exertion	Level of physical activity required to traverse the virtual mining environment.
Self rescuer oxygen consumption	The rate at which oxygen is consumed whilst using the self-rescuer is determined in accordance with the user's current level of physical exertion.

External power supply	Status of the external supply of power to the virtual mining environment
External oxygen supply	Status of the external supply of oxygen to the virtual mining environment
Refuge chamber light status	Refuge chamber light flashes green when surface supply of power and oxygen is uninterrupted, red otherwise.
Cap lamp battery consumption	The cap lamp will consume the battery more quickly on the high beam setting than the low beam setting.
Exposure to fire	Contact with fire results in physical injury or death.
Exposure to smoke	Exposure to smoke without a functioning self-rescuer equipped will result in physical injury or death after a period of approximately ten seconds or more.
Spread of smoke	Rate at which the area affected by smoke spreads outwards from the location of the smoke
Contact with refuge chamber	Successful evacuation.

4.2.9 High Visual Fidelity

Subject Matter Experts were consulted in order to identify the characteristics of the real world problem which needed to be accommodated with high visual fidelity within FUMES. Their testimony emphasised the importance of effective orientation and navigation within the Challenger mine during an emergency evacuation whilst also highlighting the need to be able to identify hazards and obstacles effectively. The characteristics to be accommodated with high visual fidelity within FUMES are listed in Table 4.14 accordingly.

Table 4.14. Characteristics to be accommodated with high visual fidelity within FUMES

Characteristic	Details
Refuge chamber	· Physical dimensions and appearance must match real world counterpart · Needs status light which can flash green or red · Requires luminescent stripes which aid visibility in low light conditions
Depth markings and escape rise reflective signage	· Depth markings need to show the depth of each level from the surface. These are painted on the surfaces of the walls using red paint on a white rectangular background. · Escape rise signage needs to indicate the direction of escape rises on each level and must also be luminescent to aid visibility in low light conditions.
Spatial characteristics of the Challenger mine	· Three-dimensional characteristics of the mining environment in FUMES must be consistent with those of the real world counterpart.
Escape rise	· Physical dimensions and appearance must match real world counterpart

Lighting and shadows	·	Dynamic lighting and shadows are required to represent the lighting conditions within the Challenger mine.
	·	Cap lamp and refuge chamber status light
Assorted infrastructure	·	Visual cues within the virtual mining environment such as vent bags and service pipes need to resemble their real world counterparts so that they can be recognised and utilised to aid orientation and navigation.
Realistic fire effects	·	Fire needs to be immediately recognisable
Realistic smoke effects	·	Smoke needs to be immediately recognisable and obscure vision as per real world smoke

4.3 Situational Design Considerations

Situational Design Considerations are incorporated into the design of a 3D problem-based learning environment to accommodate the corresponding overlapping Situational Analytical Factors which have been identified during situation analysis (Chapter 2.5). Specifically, this involves characterising the problem-solving task in relation to the real world problem and users' existing knowledge of the problem domain (Chapters 4.3.1 through 4.3.3), representing the problem-solving task authentically within the technical capabilities of the 3D simulation environment (Chapters 4.3.4 and 4.3.5), and allocating control mechanisms within the simulation which approximate the actions used to resolve the real world problem (Chapter 4.3.6).

4.3.1 Structuredness

The structuredness of the problem-solving task within FUMES was designed to accommodate the situatedness of the real world problem in addition to the existing knowledge of Dominion personnel that was instilled during induction training. To this end, the problem-solving task in FUMES was structured to reflect a real world emergency evacuation scenario at Challenger in terms of the extent of information that was provided to users. Users were informed of the need to evacuate to refuge in response to an underground fire emergency within the Challenger mining environment and were also explicitly provided with some initial information which identified their location, the location of smoke, and the location of the nearest refuge chamber within the virtual mine. However, users were not to be provided with any instruction regarding how to safely reach a refuge chamber. The problem-solving task was thus designed with a well-structured goal state, partially ill-structured initial state, and ill-structured solution method, as detailed in Table 4.15.

Table 4.15. Structuredness of the problem-solving task in FUMES

State	Details
Initial state	• Partially ill-structured • Users provided with some information in relation to their location and proximity to refuge chambers and environmental hazards
Goal state	• Well-structured • Users informed of the nature and goal of the problem-solving task within the context of an emergency evacuation of the Challenger mining environment due to an underground fire.
Solution method	• Ill-structured • Users not instructed as to how to reach a refuge chamber beyond being told to adhere to existing emergency evacuation protocols used at Challenger.

4.3.2 Complexity

The complexity of the problem-solving task was designed to embody relationships within the real world problem domain in order to accommodate its situatedness and the knowledge obtained by personnel during induction training. The relationship between actions and outcomes during problem-solving activity were specified such that contact with fire or exposure to smoke without a functioning self-rescuer would result in failure, while safe passage through the mine to a refuge chamber would result in successful evacuation. Users were given a choice of two refuge chambers to evacuate to, given that at any point within the Challenger mine, personnel would have at most one refuge chamber above them, and one below them to chose from in the event of an evacuation. Furthermore, the complexity of the problem-solving task also encompassed relationships between movement speed, terrain inclination, physical exertion, self-rescuer oxygen consumption, and cap lamp battery depletion in order to elicit participants' existing knowledge of the real world problem domain within the simulation environment. The complexity of the problem-solving task within FUMES is thus summarised in Table 4.16.

Table 4.16. Complexity of the problem-solving task in FUMES

Relationship	Details
Failed outcome	• Contact with fire • Exposure to smoke without self-rescuer for a duration exceeding ten seconds
Successful outcome	• Reaching one of two possible refuge chambers within the FUMES mining environment
Physical exertion	• Determined in accordance with the user's movement speed and the inclination of the terrain over which they are moving

	·	Climbing an escape rise requires a high degree of physical exertion
Self-rescuer	·	Allows smoke to be negotiated safely when equipped and supplying oxygen
Self-rescuer oxygen consumption	·	Determined in accordance with the user's physical exertion
Cap lamp battery depletion	·	Determined in accordance with beam setting (low or high)
Starting location	· ·	Proximity to fire and smoke Proximity to refuge chambers

4.3.3 Domain Specificity

The domain specificity of the problem-solving task in FUMES was designed to oblige participants' existing knowledge and experience and the situatedness of the real world problem, whereby problem-solving activity was situated within a spatially accurate representation of the Challenger mine during an underground fire emergency. The virtual mining environment within FUMES was thus highly contextualised and featured escape rises, refuge chambers, and visual cues such as depth markings, escape rise signs, and servicing infrastructure. Participants were also provided with a cap-lamp and self-rescuer to assist them in reaching a refuge chamber. The cues utilised to establish the domain specificity of the problem-solving task are thus detailed in Table 4.17.

Table 4.17. Domain specificity of the problem-solving task in FUMES

Cue	Details	
Challenger mining environment	· ·	Spatially accurate in three dimensions with respect to the real world mine, including the layout and configuration of the decline and drives Consistent locations of refuge chambers, escape rises, and visual cues which aid navigation and orientation
Underground fire emergency evacuation scenario	· · ·	Presence of smoke and fire. Emergency evacuation declared via radio system and also signified using stench gas Procedure for successful evacuation to refuge consistent with real world problem
Cap lamp	·	Light situated above the user's viewing perspective to simulate cap lamp which can change between low and high beam settings
Self-rescuer	· ·	Allows the user to safely negotiate smoke Takes approximately 30 seconds to equip

4.3.4 Problem Representation

The problem representation was designed to appeal to participants' existing real world experience within the Challenger mine using the technical capabilities afforded by the 3D simulation environment. An initial briefing was provided prior to the onset of problem-solving activity which explicitly established the context of the problem in terms of emergency evacuation scenarios in the Challenger mine. The problem-solving task itself was represented using a three-dimensional depiction of the Challenger mining environment during an emergency evacuation scenario in which the user was required to safely reach refuge in accordance with established evacuation protocol. Users were afforded the ability to move and orientate freely within the virtual mine and could utilise escape rises, a cap-lamp, and a self-rescuer at their discretion.

In order to expose participants to a variety of potential evacuation scenarios, the problem-solving task was represented as a series of three distinct problem-solving instances. The initial conditions of each instance were established using a series of sequential prompts which identified the user's location and that of the nearest refuge chambers in addition to their proximity to fire and smoke hazards within the virtual mine. However, in order to encourage the user to assume responsibility for their learning and the acquisition of learning resources, each problem-solving instance decreased the amount of information provided by the sequential prompts in turn. In this manner, the problem-solving task became progressively more ill-structured, complex, and domain specific with each successive instance.

In addition to the provision of sequential information prompts, the problem representation also afforded users the ability to acquire information from a variety of sources simultaneously within the virtual mining environment. Users could identify their position, proximity to hazards, and the location of the closest refuge chamber by moving around and manipulating their viewing perspective within the three-dimensional space. The problem representation can thus be summarised in Table 4.18 as follows.

Table 4.18. Representation of the problem-solving task within FUMES

Problem-solving instance	Problem statement	
	Information provided explicitly	**Information acquired via user interaction**
Initial briefing	1) Context of the problem-solving task	

1	1) Emergency evacuation declaration 2) Location of vehicle fire 3) Location of smoke 4) User's initial starting location 5) Location of nearest refuge chambers	User's location Potential environmental conditions Characteristics of the terrain Location of vehicle fire Location of smoke
2	1) Emergency evacuation declaration 2) Location of vehicle fire 3) Location of smoke	
3	1) Emergency evacuation declaration	

4.3.5 Authenticity of Information

The information provided during the statement of the problem was designed to be authentic in relation to emergency evacuation scenarios at Challenger, both in terms of the information that was provided, and the medium utilised to present it. In order to replicate the emergency broadcast system used at Challenger to notify personnel of an evacuation, auditory cues were employed under the guise of a personal radio to provide users with sequential information prompts which established the circumstances of the emergency and the need to evacuate to refuge. Table 4.19 outlines the information presented using auditory cues during the problem statement accordingly:

Table 4.19. Authentic information provided during the problem statement in FUMES

Information provided during the problem statement	Auditory cue
Emergency evacuation declaration	Audio cue declaring an emergency evacuation
Location of vehicle fire	Audio cue identifying the depth level at which the presence of a vehicle fire has been reported
Location of smoke	Audio cue identifying the depth level at which the presence of smoke has been reported
User's initial starting location	Audio cue announcing the depth level of the mine that the user begins the problem-solving instance on
Location of nearest refuge chambers	Audio cue announcing the depth levels of the closest refuge chamber to the user's initial starting location

4.3.6 User Control

The control mechanisms implemented within the 3D simulation environment were designed to reflect those that would be utilised to resolve the real world problem. Users were provided with the ability to move and orientate themselves freely within the virtual mine, with added abilities included for climbing escape rises, equipping a self-rescuer, and changing the beam intensity on

their cap lamp. The control mechanism afforded to the user are designated in Table 4.20.

Table 4.20. User abilities and associated control schemes within the simulation environment

User ability	Control scheme
Movement	Move forwards or backwards, sidestep left or right, at walking or running pace. Walking speed is approximately 5 km/h. Running speed is approximately 10 km/h.
Orientation	Change the viewing perspective, which also changes the focal point of the cap lamp beam. The speed with which the viewing perspective can be moved should reflect what is possible in the real world environment.
Climb escape rise	Ascend or descend a vertical, twenty metre ladder span between levels of the mine. This takes approximately 45 seconds.
Put on self rescuer	Equip self rescuer, which takes approximately 30 seconds.
Change beam setting on cap lamp	Change from low to high beam setting, and vice versa

4.4 Problem-based Learning Design Principles

Problem-based Learning Design Principles are the core tenants which guide the learning process (Chapter 2.5). They are utilised in concert with the Situational Analytical Factors and Situational Design Considerations that have been established to characterise learner control (Chapter 4.4.1), information (Chapter 4.4.2), feedback (Chapter 4.4.3), assessment (Chapter 4.4.4), and reflection (Chapter 4.4.5) within the learning environment.

4.4.1 Learner Control

Control of the learning process was designed to be shared between the simulation environment and the user in accordance with the SUPL Design Framework. FUMES was designed such that the user exercised learning control in terms of the method that they chose to resolve the problem. The user was was free to move and orientate their viewing perspective at will and could employ their cap lamp and self-rescuer at their discretion within the virtual mine (Chapter 4.3.6). In this manner, the user made decisions as to how they navigated through the virtual mine and the route they took to refuge, in addition to the circumstances under which they employed their cap lamp and self-rescuer to this end.

FUMES was also designed to provide the user with control of the learning process in terms of

the acquisition of information needed to resolve the problem. The simulation did not provide nor explicitly identify sources of information which needed to be utilised to safely evacuate to refuge within the virtual mine (see Chapter 4.4.2). Furthermore, the user was forced to assume increasing responsibility for the acquisition of information as each problem-solving instance was ill-structured, complex, and domain specific than the one that preceded it (Chapter 4.3.4). In this manner, FUMES was designed to slowly seed control of the learning process to the user over the series of three problem-solving instances.

Conversely, the structuredness, complexity, and domain specificity of each problem-solving instance was dictated by the simulation environment (Chapters 4.3.1, 4.3.2, 4.3.3, and 4.3.4). In this manner, FUMES controlled the circumstances of each learning scenario in terms of what users were subjected to by specifying their initial starting location and proximity to refuge chambers, smoke, and fire.

FUMES was also designed to provide users with facilitatory support to help control the learning process as is recommended in learning scenarios in which responsibility for the learning process is shared (Charlin et al., 1998; Johnson et al., 1999). Facilitatory support was used to guide the user as they utilised their existing knowledge of emergency evacuations at Challenger to evacuate to a refuge chamber within the virtual mine and achieve problem resolution. As facilitatory interaction was tied to specific user behaviour as a feedback mechanism, this is detailed under the design of Feedback in Chapter 4.4.3.

4.4.2 Information

In accordance with the SUPL Design Framework, FUMES was designed to provide users with information which they could use to address the learning needs of the problem. This information was presented in the form of the virtual mining environment, whereby users could manipulate their position and viewing perspective to maintain situational awareness during problem-solving activity. In this manner, the provision of information within FUMES was designed such that users assumed responsibility for acquiring the information which was used to resolve the problem. Users were not informed explicitly as to their location within the mine and needed to determine this via their own interaction. However, in order to overcome their lack of experience within the Challenger mining environment, Novice Participants were provided with a separate Mine Layout Diagram which they were able to reference as they used the simulator. The

information provided by FUMES to address the learning needs of the problem is summarised in Table 4.21 accordingly.

Table 4.21. Information provided within the virtual mine which addressed the learning needs of the problem

Information	Procurement
Orientation and situational awareness	User is required to manipulate their viewing perspective in order to determine the direction they are facing within the virtual mining environment. This will also allow the user to work out their proximity to any nearby environmental hazards such as smoke or fire within the virtual mine.
Location	User is required to make use of spatial cues within the virtual mining environment as they move and orientate themselves within it in order to maintain locational awareness.

4.4.3 Feedback

Using the SUPL Design Framework, feedback provided by FUMES was designed to guide the user's ability to utilise their existing knowledge to achieve problem resolution in a manner that was consistent with real world problem interaction. The technical affordances of the 3D simulation environment were utilised to provide feedback at both the facilitator and task environment level, whereby auditory cues presented under the guise of personal radio communications were used to approximate a facilitator construct, while feedback provided by the task environment was incorporated into the virtual mining environment.

The facilitator construct was designed to respond to specific user behaviour with auditory cues which provided direct instruction or questioned user behaviour for the purpose of guiding the problem-based learning process. This facilitatory feedback is outlined in Tables 4.22 and 4.23, respectively.

Table 4.22. Feedback provided by the facilitator construct which issued direct instructions

User behaviour	Response provided via facilitator construct	Impact
User continues to head in the wrong direction	Tells the learner that they are headed in the wrong direction and to turn around immediately	Learner turns around and knows that their objective is not in the direction that they were previously heading
User encounters smoke and is in danger of dying because	Tells the learner to equip their self-rescuer immediately or they will	Learner equips their self rescuer

they have not equipped their self-rescuer	succumb to the smoke	
User getting too close to a vehicle fire	Tells the learner that they are getting too close to the fire	Learner re-assesses their current bearing
Remaining self-rescuer capacity	Tells the learner when their self-rescuer gets to 50%, 10%, and 0% oxygen capacity respectively	Learner attempts to reach a refuge chamber as soon as possible
Interruption of external oxygen and power supplies	Tells the learner that external supplies of oxygen and power have been interrupted	Learner knows that the refuge chamber lights will be red instead of green

Table 4.23. Feedback provided by the facilitator construct which questioned user behaviour

User behaviour	Response provided via facilitator construct	Impact
User heading in the wrong direction	Asks the learner if they are sure they are heading in the right direction	Learner re-assesses their current bearing
User encounters smoke	Asks the learner what they should do when they first encounter smoke	Learner considers the appropriate course of action based on their induction training
Use of escape rise	Asks the learner whether it was necessary to use the escape rise	Learner considers whether it was necessary to climb the escape rise in order to reach a refuge chamber

Feedback provided at the task environment level was used to provide users with a believable representation of the Challenger mining environment which approximated real world interaction during an emergency evacuation. Users were provided with feedback which described their moment and physical interaction as they moved through the virtual mine and were also kept apprised as to the status of their self-rescuer and cap lamp, their exposure to environmental hazards, and the condition of external power and oxygen supplies. This allowed them to undertake the problem-solving task in a manner that was similar to real world activity during an emergency evacuation of the Challenger mine. Table 4.24 outlines the feedback provided to users within the task environment accordingly.

Table 4.24. Feedback provided to users by the task environment

Type of information	Description	Impact
Movement speed	Feedback to represent footsteps within the virtual mine that is provided in response to the user's movement speed and the terrain that they are traversing. Feedback is also provided to restrict the user from running if	Assists the learner in developing a sense of perspective, scale and the relative distances involved within the Challenger mine. The learner is also encouraged to understand that running with a self-rescuer

	their self-rescuer is equipped.	equipped is not advisable during a real world emergency.
Terrain inclination	Informs the user as to the current slope of the terrain	Alerts the learner as to whether they are ascending or descending as they move through the mine
Physical exertion	Level of physical activity required to traverse the virtual environment dependent on the inclination of the terrain and the user's movement speed	Assists the learner in understanding that their movement speed and the nature of the terrain affect physical exertion. Assists the learner in understanding that physical exertion affects their breathing rate, and in turn, the level of oxygen being consumed if they are using their self rescuer.
Self rescuer activation status	Learner has activated the self rescuer	Informs the learner that their self rescuer needs to be equipped in order to move through areas of the mine where smoke is present Provides the learner with a sense of how long it takes to put on a self rescuer
Oxygen supply in self rescuer nearing depletion	The supply of oxygen available in the self rescuer is nearly exhausted	Assists the learner in developing an understanding as to the capacity and capabilities of the self rescuer Assists the learner in recognising the importance of reaching a refuge chamber as quickly and efficiently as possible
Cap lamp status	User changes the cap lamp beam setting between low and high	Assists the learner in developing an understanding as to the capabilities of the cap lamp
External power supply failure	External power supplied to the mine is interrupted	Informs the learner that power is normally delivered from the surface, but that this supply can be interrupted during a fire underground
External oxygen supply failure	External oxygen supplied to the mine is interrupted	Informs the learner that oxygen is normally delivered from the surface, but that this supply can be interrupted during a fire underground
Climbing of escape rises	The user is close enough to an escape rise to climb it	Assists the learner in developing a sense of how close they need to be to an escape rise in order to climb it
Stench gas detected	The user has detected the smell of the stench gas system	Assists the learner in understanding the ways in which

		an emergency evacuation of the mine can be ordered
Personal radio communication	Informs the learner when their personal radio is being used to provide information	Assists the learner in understanding the ways in which an emergency evacuation of the mine can be ordered

Establishes the initial conditions and known information at the onset of each problem-solving instance |
Exposure to smoke	Informs the learner when they are exposed to smoke without a functioning self rescuer equipped	Informs the learner that they need to equip their self rescuer in order to safely negotiate areas of the mine in which smoke is present
Exposure to fire	Informs the user when they have made contact with a vehicle fire, thus ending the problem-solving instance	Informs the learner that they must not make contact with a vehicle fire during an emergency evacuation
Orientation and movement	Informs the user of their orientation and location within the virtual mining environment. The three-dimensional visual display of the virtual mine is updated dynamically as the user moves or manipulates their viewing perspective.	The learner is free to develop spatial representations of the mining environment and determine their own approach for evacuating to a refuge chamber.

4.4.4 Assessment

In accordance with the SUPL Design Framework, assessment mechanisms within FUMES were designed to evaluate users' ability to adhere to the established emergency procedures used at the Challenger mine in order to encourage the development of strategies which would be applicable during a real world evacuation. The metrics used to assess user performance outlined in Table 4.25 were presented at the conclusion of each problem-solving instance in order to allow users to gauge their performance in accordance with the SUPL Design Framework.

Table 4.25. Assessment measures within FUMES

Assessment measure	Criteria	Impact
Outcome of the problem-solving instance	The problem-solving instance is deemed a success if the user is able to reach a refuge chamber. It is deemed a failure if the user makes contact with a vehicle fire or if the user is exposed to smoke for 30 seconds without a functioning self-rescuer	· Reiterates the primary objective during an emergency evacuation
Elapsed time	A timer is initialised at the onset of each	· Highlights the

	problem-solving instance and runs until an outcome has been reached		•	importance of evacuating as efficiently as possible • Provides a sense of the scale of the mining environment
Physical exertion	Total physical exertion for the problem-solving instance is deemed low if the user predominantly walked through the virtual mine, moderate if they ran some of the distance, and high if they ran and climbed a number of escape rises		•	Encourages the learner to get to a refuge chamber as efficiently as possible • Provides an indication as to the relationship between movement speed, the inclination of the terrain, and physical exertion
Distance travelled	The distance travelled by the user during a problem-solving instance is measured up to the point where an outcome is reached.		•	Highlights the importance of evacuating as efficiently as possible • Provides a sense of the scale of the mining environment
Remaining self-rescuer capacity	The remaining self-rescuer capacity is expressed as a percentage and depleted according to the user's physical exertion		•	Highlights the importance of evacuating as efficiently as possible • Provides an indication as to the operational capacity of the self rescuer
Remaining cap lamp capacity	The remaining cap lamp capacity		•	Provides an indication as to the operation capacity of the cap lamp
Refuge chamber selected	Refers to which refuge chamber was reached by the user for a given problem-solving instance. Each problem-solving instance has an ideal refuge chamber given the user's starting position and the environmental conditions within the virtual mine		•	Reiterates the emergency evacuation procedure at Challenger
Path taken	Details whether or not the user has taken the ideal path to their selected refuge chamber. The ideal path for each problem-solving instance requires the user to only use an escape rise when the decline is		•	Reiterates the emergency evacuation procedure at Challenger

	obstructed, and to stay on the decline at all other times as per Dominion procedure.	• Encourages the learner to get to a refuge chamber as efficiently as possible • Provides information on the layout of the Challenger mine
Escape rise usage	Details whether or not the user has made appropriate use of escape rises during a given problem-solving instance. Escape rise usage is only appropriate where a fire is blocking the decline and the only way around it to a refuge chamber lies in the use of an escape rise	• Reiterates the emergency evacuation procedure at Challenger
Self-rescuer usage	Details whether or not the user equipped their self-rescuer and whether this was necessary given the conditions within the environment for a given problem-solving instance	• Reiterates the emergency evacuation procedure at Challenger

4.4.5 Reflection

Opportunities and support for reflection were integrated into the design of FUMES using the SUPL Design Framework in the form of explicit question prompts which were presented to the user at the conclusion of each problem-solving instance. These explicit question prompts differed according to the outcome achieved by the user and were designed to complement the question prompts posed by the facilitator construct to encourage reflection on the strategies for learning, as well as what was learned and how it could be reapplied in future situations (Grunefeld & Silen, 2000; Hmelo-Silver, 2004; Savery & Duffy, 2001). These reflective question prompts are detailed in Tables 4.26, 4.27, and 4.28 for each problem-solving instance.

Table 4.26. Reflective questions posed at the conclusion of the first problem-solving instance

Reflective Questions	Context
• Which factors are important in choosing the ideal refuge chamber during an emergency evacuation? • Which route through the mine provides the safest and most efficient access to refuge chambers? • Why do you think that it is important to evacuate to a refuge chamber using minimal physical effort? • When is it appropriate to use escape rises during an emergency evacuation? • When is it appropriate to equip your self-rescuer during an emergency evacuation?	User successfully reaches a refuge chamber

Table 4.27. Reflective questions posed at the conclusion of the second problem-solving instance

Reflective Questions	Context
• Which factors do you consider when choosing which refuge chamber to evacuate to during an emergency? • Which route provides the safest and most efficient access to this refuge chamber? • What impact does your level of physical effort have on the duration of oxygen supply provided by your self-rescuer? • What is the preferred method for clearing blockages to the main decline? • When should you equip your self-rescuer during an emergency evacuation?	User successfully reaches a refuge chamber
• When should you equip your self-rescuer during an emergency evacuation? • What impact does your level of physical effort have on the duration of oxygen supply provided by your self-rescuer? • How can you best manage your self-rescuer in order to prolong the supply of oxygen? • Which route provides the safest and most efficient access to refuge chambers? • What degree of impact does climbing escape rises have on the duration of oxygen supplied by your self-rescuer?	User succumbs to smoke, resulting in failure
• Under which circumstances should use of the main decline be avoided? • How can blockages on the main decline be cleared? • Which route provides the safest and most efficient access to refuge chambers? • What environmental cues indicate the presence of fire? • When should you equip your self-rescuer during an emergency evacuation?	User makes contact with fire, resulting in failure

Table 4.28. Reflective questions posed at the conclusion of the third problem-solving instance

Reflective Questions	Context
• Which environmental cues can be used to determine your location within the mine? • How can knowledge of the slope of the terrain assist in navigating towards a refuge chamber during low visibility conditions? • Which environmental cues indicate the interruption of air and power supplied to the mine from the surface? • What is the preferred direction of travel along the decline during an emergency evacuation? • When is it appropriate to travel in the opposite direction?	User successfully reaches a refuge chamber
• Which environmental cues can be used to determine your location within the mine? • How can knowledge of the slope of the terrain assist in navigating towards a refuge chamber during low visibility conditions? • At what point should you equip your self-rescuer during an emergency evacuation? • How does physical effort affect the duration of oxygen supply provided by your self-rescuer? • How can you best manage your level of physical effort in order to prolong the supply of oxygen?	User succumbs to smoke, resulting in failure
• Which environmental cues can be used to determine your location within the mine? • How can knowledge of the slope of the terrain assist in navigating towards a refuge chamber during low visibility conditions? • Which route provides the safest and most efficient way to reach refuge chambers within the mine?	User makes contact with fire, resulting in failure

> - Under which circumstances should use of the main decline be avoided?
> - How can blockages on the main decline be cleared?

4.5 Summary for Designing the 3D Simulation Environment

FUMES was designed as a training platform for mining personnel to develop knowledge and skills needed during emergency evacuations of the Challenger mine. This was undertaken via the delineation of Situational Analytical Factors, Situational Design Considerations, and Problem-based Learning Design Principles in accordance with the SUPL Design Framework to facilitate transferable learning. A context for learning and learning objectives for the simulation was established through information provided by Subject Matter Experts at Challenger in order to inform the design process.

Situational Analytical Factors were defined using information provided by Subject Matter Experts at Challenger in order to identify the contextual factors which needed to be accommodated by FUMES. As a result of mandatory induction training at Challenger, a common foundation of prior knowledge, domain knowledge, and structural knowledge was identified amongst mining personnel. It was also determined that emergency evacuation scenarios at Challenger were highly contextualised activities owing to the unique spatial characteristics of the mining environment and the particular emergency evacuation procedure practised at Challenger. In order to represent this problem, the 3D simulation environment needed to provide an authentic and spatially accurate representation of the Challenger mining environment featuring refuge chambers, escape rises, consistent environmental conditions, and visual cues depicted with high visual fidelity. Furthermore, users needed to be able to interact within this space in a manner which approximated real world activity regarding movement, orientation, and application of a cap lamp and self-rescuer.

Situational Design Considerations were delineated in accordance with the Situational Analytical Factors, established to provide users with the leverage to develop transferable problem-solving knowledge. The problem-solving task was situated within the context of an underground fire emergency in the Challenger mine, whereby users would be tasked with evacuating in accordance with Dominion protocol. Problem structure was designed to reflect the extent of information available during a real world emergency evacuation scenario at Challenger,

whereby users were explicitly informed as to the nature of the emergency, but not the method required for resolution. Similarly, problem complexity embodied relationships that were consistent with those present in the real world problem domain in terms of the association between actions and outcomes and physical exertion and oxygen consumption. The problem-solving task was represented as a series of three problem-solving instances which became successively more ill-structured, complex, and domain specific in turn. Authentic means of information dispersal were employed to approximate that emergency evacuation broadcast system used in the real world mine, whilst the user was provided with means of interaction which were analogous to the actions undertaken during a real world emergency.

Problem-based Learning Design Principles were characterised to support the learning process in a manner that was consistent with the Situational Analytical Factors and Situational Design Considerations that had been constituted. Control of the learning process was shared, with FUMES dictating the circumstances of each problem-solving instance, and the user assuming control over their approach to resolution and responsibility for the acquisition of information within the virtual mine. FUMES also provided a facilitator construct to help guide the learning process which issued direct instructions and question prompts as auditory cues in response to specific user behaviour. Additional sources of feedback were provided within the task environment to establish a functionally believable representation of the Challenger mining environment during an emergency evacuation. Assessment mechanisms were tied to real world performance measures for emergency evacuations of the Challenger mine in order to encourage users to monitor their performance and develop strategies and behaviours that would be transferable. These were presented at the conclusion of each problem-solving instance in addition to reflective question prompts, the contents of which differed according to the outcome of the problem.

While this chapter has described the implementation of the SUPL Design Framework for emergency evacuation training in an underground mining facility, it is important to note that the SUPL Design Framework is being proposed as a framework for the design of 3D simulation environments beyond this immediate context. The SUPL Design Framework emphasises the development of knowledge that is applicable beyond the immediate context in which it was learned in accordance with a problem-based learning pedagogy, and as such, can be potentially utilised in a variety of contexts in which the development of problem-solving knowledge for real world application is desirable. Subsequent chapters (see Chapters 6, 7, 8, and 9) will explore whether the SUPL Design Framework can be instantiated beyond this instance via

analysis of the data collected during the study to verify it's efficacy as a design framework. The technical development of FUMES in accordance with the design established from the SUPL Design Framework is documented in the next chapter.

5 Developing the 3D Simulation Environment

The previous chapter documented the design of the FUMES training platform in accordance with the SUPL Design Framework. FUMES was designed to develop the knowledge and skills of mining personnel that were necessary for emergency evacuation of the Challenger mine. This was undertaken to address the research questions proposed by this study which explored the viability of gaming technologies to satisfy real world training requirements, and the efficacy of the SUPL Design Framework to guide the development of 3D simulation environments within this capacity.

This section describes the technical development of FUMES based on the design derived in Chapter 4, with discussion including:

- Chapter 5.1 - Identification of relevant game engine criteria in accordance with the established design. This is followed by an examination of appropriate 3D game engines in light of this criteria and the selection of the DX Studio 3D game engine for development.
- Chapter 5.2 - Implementation of the design established in Chapter 4 using the DX Studio 3D game engine. This discussion details the development of the virtual mine, integration of the problem-solving task, guidance of the learning process, and the known limitations and compromises in the implementation of the design, and;
- Chapter 5.3 - A post development analysis of the DX Studio 3D game engine.

5.1 3D Game Engine Selection

Several 3D game engines were considered for the the implementation of FUMES. Criterion was established to aid in their evaluation based upon the design established in Chapter 4, as detailed in Table 5.1:

Table 5.1. Game engine criteria required to instantiate FUMES

Capability	Description
Development suite	The selected game engine needs to be packaged as part of a development suite such that content can be easily imported and arranged to be rendered by the game engine. This development suite should be feature rich and user friendly in order to support a rapid prototyping approach due to the time constraints imposed by the study.
Scripting	The selected game engine will require scripting support in order to implement the functional aspects of the simulation.
External 3D model support	The selected game engine and accompanying development suite will need to support external 3D modelling file formats so that dedicated modelling software can be used to develop assets for the simulation.
Texture mapping	The selected game engine will need to support diffuse, bump, normal, and reflective or emissive maps. The development suite will need to provide capabilities to directly add these maps to 3D model assets.
Physics	The selected game engine will require basic physics support in order to detect collisions between objects.
Lighting	The selected game engine will require the ability to support multiple light sources concurrently, including lights that can move within the simulation environment.
Shadows	The selected game engine will require the ability to render dynamically generated shadows in real time.
Animated sprites	The selected game engine will require support for 2D sprites in order to represent smoke and fire. The game engine will also need to be able to render fog at varying degrees of intensity.
Audio	The selected game engine will require the ability to associate audio samples with objects or events. Directional audio support would also be beneficial.
Low software cost	The cost for licensing of the game engine to be less than $500 AUD
Performance and system requirements	The selected game engine should be optimised to run on a moderate desktop PC in order to minimise hardware costs.

Several potential game engines with the ability to represent 3D spaces were compared according to the required game engine features listed in Table 5.1. Tables 5.2 and 5.3 detail comparisons between the 3D game engines under consideration accordingly.

Table 5.2. Comparison of features amongst potential 3D game engines

Game Engine	Criteria				
	Development suite	Scripting	External model support	Texture mapping	Physics
S2 Engine	- WorldEditor - SceneStudio - MaterialEditor - ModelStudio	C++	COLLADA	Two texture map and bump map channels per object	Collision detection, including for particles
Visual 3D.NET	- Model, Material, and Animation Editors - EarthBuilder Toolset - Object Editor - Physics and GUI Design Modes - Particle, Behavior, and Time Line Editors	C#, VB.NET, IronPython, Lua.NET	Ogre (.mesh), Collada (.dae), (.x)	Multi-texturing, bump mapping, mipmapping, volumetric, projected, procedural	Collision detection, rigid body, vehicle physics
DX Studio	- Complete 2D and 3D scene editors	Javascript	DXMesh format with plugin for common 3D modelling packages	Basic, multi-texturing, bumpmapping, mipmapping, volumetric, procedural	Collision detection, rigid body, vehicle physics
C4 Engine	- World Editor - Script Editor - Shader Editor - Interface Editor	Graphical scripting editor, C++	COLLADA	Bump, mipmapping, custom shader support	Third-party
Torque Game Engine Advanced	- World Editor - Terrain Editor - Terrain Generator - GUI Editor	C++ like syntax	COLLADA	Basic, multi-texturing, bumpmapping, mipmapping, volumetric	Collision detection, rigid body, vehicle physics

Table 5.3. Continued comparison of features amongst potential 3D game engines

Game Engine	Criteria					
	Lighting	Shadows	Animated sprites	Audio	Cost	Performance and system requirements
S2 Engine	Omnidirectional, spot, directional, and global lighting with	Dynamic shadows with support for soft shadows	Post-processing	3D sound	$230.00	- 2Ghz Dual Core processor - 2 GB RAM - OpenGL 2.0 compatible

	mapping and projection support					NVIDIA Geforce8 8600/8800 or ATI HD2600/HD2900 graphics cards - Windows2000/XP operating system - OpenAL compatible sound card
Visual 3D.NET	Diffuse, specular, and emissive light sources.	Shadow mapping, real time shadows, shadow fade outs.	Particle system, fire, explosion, decals, fog.	3D sound, streaming sound	$232.00	- Shader Model 3.0 capable graphics card or higher - NVIDIA 9600GT, ATI HD 4670 or higher - 2 GB RAM or more - 2 GHz Dual Core Processor or better
DX Studio	Per-vertex, per-pixel, lightmapping, radiosity, gloss maps, anisotropic	Shadow mapping, shadow volume	Particle system, fire, explosion, decals, fog.	2D sound, 3D sound, streaming sound	$200.00	- 2GHz Windows 2000/XP/Vista PC - 1Gig RAM - DirectX 9.0c compatible video card
C4 Engine	Dynamic lighting	Dynamic shadows	Volumetric fog, procedural fire, particle system	3D sound, directional sounds, streaming sound	$420.00	- GeForce 6600 or higher - Radeon X1300 or higher - Latest version of DirectX (March 2009 or later)
Torque Game Engine Advanced	Per-vertex, per-pixel, volumetric, lightmapping, radiosity	Shadow mapping, projected planar, shadow volume	Particle system, decals, fog	2D sound, 3D sound, streaming sound	$350.00	- Video card must support Shader model 1.0 or above

Several of the game engines under consideration satisfied the evaluation criteria. In order to narrow down the list of choices, trial versions of each 3D game engine were evaluated to provide a more experiential appraisal of their features. Based on these evaluations, DX Studio was chosen as the 3D game engine to develop FUMES.

Initial exploration of the DX Studio development suite indicated that content could be easily imported and configured via the 2D and 3D scene editors that were integrated into the development environment. Each scene editor allowed imported assets to be instantiated as objects which could be acted upon or modified without affecting the originals. Using the 2D and 3D scene editors, a simple prototype featuring a single refuge chamber model was developed

very quickly, indicating that the DX Studio development suite would be well suited to an agile development approach. This was a key consideration given the scant six months allocated for the implementation of FUMES during the study.

Each object instantiated from an asset within DX Studio had the ability to have a script associated with it, providing support for an object-orientated approach to development. In this manner, variables and functions could be associated with a particular object within the simulation environment and acted upon accordingly as circumstances required. While the scripting interface was very basic, it nonetheless appeared capable of sequencing instructional content and modelling behaviours and responses between objects within the simulation environment.

The trial version of DX Studio also included a set of export plugins for common external modelling packages such as 3D Studio Max, Blender, and Google SketchUp which exported model data in a native DX Studio file format. The 3D Studio Max plugin was tested and found to work correctly, thus providing the capability for the required 3D assets to be developed in a dedicated modelling package before being imported into the simulation environment.

Exploring the DX Studio trial also revealed support for a variety of texture maps which could be assigned to 3D model assets via the in-built material editor. In this manner diffuse, normal, bump, reflection, opacity, specular, and emissive maps could be assigned to a 3D model in a variety of common image formats.

Support for physics was integrated into the 3D scene editor for objects via a configurable parameter that could be enabled or disabled as required. Enabling the physics property for an object ensured that no other object could pass through it whilst also subjecting the object to the effects of gravity. This provided the means to establish authentic player control within the simulation environment.

The DX Studio platform supported a number of different dynamic lighting types, including spotlights which could be used to represent the cap lamp, all of which could be configured or acted upon in much the same way as any other object within the 3D scene editor. In addition to these dynamic lights, DX Studio also featured an ambient light property which could be used to set the level of background lighting within a given 3D scene. A combination of dynamic lights and ambient lighting could thus be used to represent the lighting conditions within the real

world mine.

Similar to the way in which physics was integrated within the DX Studio trial, real-time shadows could also be enabled or disabled for objects within a 3D scene as required. This provided an effective means by which dynamic shadows for the player model could be implemented within the virtual mining environment without the need for additional work or development.

The DX Studio platform had provisions for the fire and smoke effects required by the simulation design by virtue of its support for 2D sprites. Simple 2D sprites could be added to a 3D scene to approximate fire and smoke using animated gifs which could be set to loop indefinitely. Furthermore, the basic fog functionality provided by DX Studio could be used to approximate the manner in which smoke spread throughout the mining environment.

Audio playback in DX Studio included support for common file formats such as wav, aiff, mp3, and ogg. Sound samples could be imported as assets and then called via script when playback was required, or associated with an object within the 3D scene in order to provide directional audio. In this manner, directional audio cues could be attached to relevant objects within the virtual mining environment to facilitate spatial and situational awareness.

The licensing costs and hardware requirements for the DX Studio platform were also among the most moderate of the potential game engines being considered for the implementation of FUMES. Furthermore, the non-commercial DX Studio license on offer did not restrict any features or functionality of the game engine.

An evaluation of the DX Studio trial software indicated that the platform was suitable for the implementation of FUMES based on the design established in Chapter 4. Of particular note was the ease with which content could be imported and arranged using the development suite, the technical requirements, such as dynamic shadows and physics, which could be implemented with minimal effort, as well as its overall cost effectiveness.

5.2 Implementation of the Design

Using DX Studio as the selected 3D game engine, the design established in Chapter 4 was implemented over a period of six months. This included the development of assets, such as 3D

models, 2D images and textures, and auditory resources, the integration of these assets within FUMES, and the application of scripts to provide necessary functionality. This process consisted of three main stages: the construction of the virtual mine (Chapter 5.2.1), the integration of the problem-solving task (Chapter 5.2.2), and the incorporation of components to guide the problem-based learning process (Chapter 5.2.3). Limitations in the implementation of the design were also identified and acknowledged during development (Chapter 5.2.4).

5.2.1 The Virtual Mine

The virtual mine in FUMES was developed as a physically and functionally accurate 3D representation of the Challenger mine in order to appeal to participants existing knowledge of the real world problem environment using the technical capabilities of DX Studio. The virtual mine embodied spatial characteristics and visual cues that were consistent with its real world counterpart, and included 3D models of refuge chambers and escape rises. Depth markings and escape rise signage were also integrated into the virtual mine to aid navigation. Lighting conditions within the virtual mining environment were designed to replicate those within the real world mine by attaching a spotlight to the player within DX Studio to approximate the cap lamps worn by mining personnel. 2D sprites were used to represent fire and smoke within the virtual mine in association with rendered fog, which approximated the spread of smoke and subsequent visual attenuation.

Scripting was used within DX Studio to provide the functionality necessary for user interaction and instantiate the relationships between entities within the problem domain, which included movement, orientation of the viewing perspective, climbing escape rises, and activation of the cap lamp and self-rescuer. Mechanisms for approximating physical exertion, self-rescuer oxygen consumption, and cap-lamp battery depletion were also implemented via scripting within DX Studio.

5.2.1.1 Spatial Characteristics

AutoCAD data supplied by Dominion was used to develop the 3D model of the mining environment so that the scale, dimensions, and spatial relations of the Challenger mine could be replicated accurately. The 3D model of the mine that was developed from this data was subsequently trimmed in order to concentrate user activity in a smaller section of the mine and speed up development time. To this end, the mine model spanned levels 860 to 740 which was

the smallest section of the mine in which two refuge chambers were located. Some side shafts were also removed from the model in order to restrict the user's movement to areas of the mine that were not too far removed from the decline, escape rises, and refuge chambers, as shown in Figure 5.1.
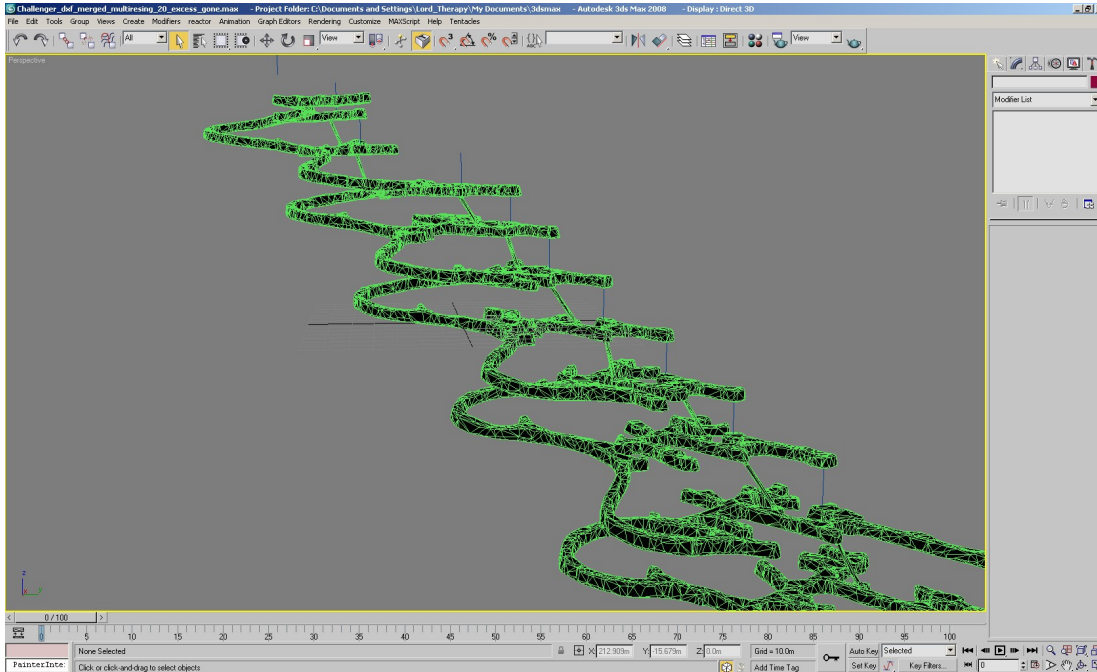
Figure 5.1. Trimmed 3D model of the mine as modelled in 3D Studio Max

Diagrams of the Challenger mine were also used to inform the locations of escape rises and refuge chambers within the virtual mine. Refuge chamber models were placed on levels 860 and 740, while escape rise models were located on each level in the side shafts near the main decline. In this manner, participants were able to rely on existing knowledge of refuge chamber and escape rise locations at Challenger within the virtual mine.

5.2.1.2 Visual Cues

The visual cues identified as potential aides to way-finding and navigation detailed in Table 4.4 were implemented such that their locations and the spatial information that they provided were consistent with their real world counterparts.

- The depth markings and escape rise signage were positioned relative to their real world counterparts within the Challenger mine using photographs and captured video footage

for reference. The development of these visual cues is discussed in greater detail later in this section (Chapter 5.2.1.5).

- The refuge chamber lights were represented by attaching red and a green light objects to the refuge chamber models within DX Studio. These light objects were then scripted to flash periodically according to whether or not external supplies of power and oxygen were operational within the virtual mine.

- After some deliberation, it was decided not to include jumbo boxes within the virtual mine, Dominion indicated that there was only two jumbo boxes in the section of the mine between levels 860 and 740, both of which were located on level 740. As these jumbo boxes were located right at the boundary of the section of the mine being modelled, and because more specific information regarding their exact location was not available during development, it was decided not to include them within the virtual mine. This omission is acknowledged as a limitation of FUMES in Chapter 5.2.4.

Simple overhead piping models which approximated the servicing pipes present within the Challenger mine were also integrated into the virtual mine. However, due to time constraints these models were quickly developed from the AutoCAD data and situated in all shafts within the virtual mine (Figure 5.2), instead of just those that featured servicing pipes in the real world mine. Time constraints also resulted in vent bags and other ventilation related equipment present at Challenger not being included within the virtual counterpart. These omissions are acknowledged as limitations of FUMES in Chapter 5.2.4.

Figure 5.2. Servicing infrastructure within the virtual mine

5.2.1.3 Refuge Chambers

The twelve person refuge chamber model was constructed to scale according to manufacturer's dimensions (see http://www.minearc.com.au) with a width of 2310 mm, a length of 4900 mm, and a height of 2370 mm. Surface materials for the model were developed with reference to images captured from within the Challenger mine and those provided via the manufacturer's website, with emissive properties used within DX Studio to replicate the piercing nature of the refuge chamber lights. Figures 5.3 depicts a refuge chamber model situated within the virtual mine.

Figure 5.3. Refuge chamber within the virtual mine

5.2.1.4 Escape Rises

The escape rise models were developed from images and video footage from the Challenger mine in order for them to be easily recognisable and appear as authentic as possible within the virtual mining environment. As with the refuge chamber lights and escape rise signage, emissive properties were associated with the arrow signs on the escape rise models in order to create the illusion of reflective surfaces. Figures 5.4 and 5.5 depict an escape rise within the real world environment and virtual mine respectively.

Figure 5.4. An escape rise within the Challenger mining environment

Figure 5.5. An escape rise within the virtual mining environment

The process for users to climb escape rises was simplified as a result of the limited time allocated for development and the technical demands involved in animating the player character model for this purpose. When climbing an escape rise, the user was presented with a pre-rendered animation of this activity from a first person perspective, as detailed in Figure 5.6. The time taken to undertake this process was accelerated in the interests of maintaining user interest. However, supplemental textual prompts were used to explicitly state how long it would take to

climb the full span of a real escape rise in the Challenger mine.
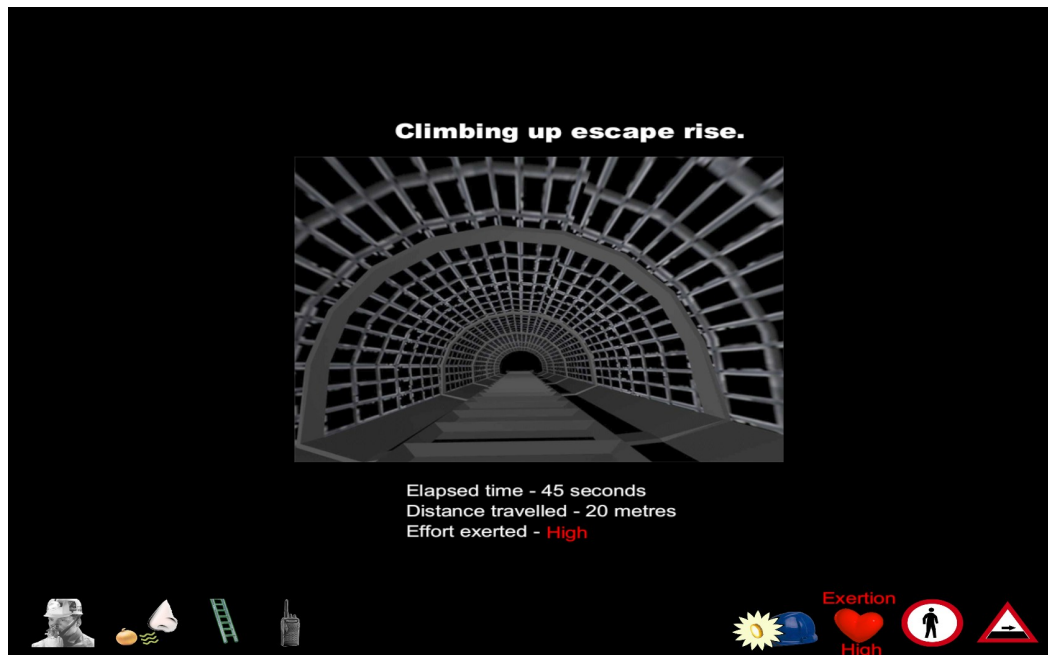
Figure 5.6. Pre-rendered animation used to denote when the user was climbing an escape rise

5.2.1.5 Depth Markings and Escape Rise Signage

Recognisable textures were required for the depth markings and escape rise signage in order for these objects to act as salient visual cues to way-finding and navigation within the virtual mining environment.

Information supplied from Dominion was used to determine at which depth marking signs would be required within the section of the mine that had been modelled. The textures used to represent these depth marking signs were then hand painted in Photoshop in order to replicate the manner in which the real world depth markings had been spray painted onto the wall surfaces within the mine. A depth marking within the Challenger mine is detailed in Figure 5.7, while Figure 5.8 depicts a depth marking within the virtual mine.

Figure 5.7. Depth marking within the real world Challenger mining environment

Figure 5.8. Depth marking within the simulation environment

The reflective nature of the escape rise signs were represented via the association of emissive properties with the textures being used to create the illusion of reflected light. Figures 5.9 and 5.10 demonstrate how emissive properties were used in DX Studio to replicate the way in which light reflected off the escape rise signs within the Challenger mining environment

Figure 5.9. Light reflecting off an escape rise sign within the Challenger mining environment

Figure 5.10. Application of emissive properties to approximate the reflective properties of escape rise signs

5.2.1.6 Lighting and Shadows

The virtual mine was illuminated using lighting objects native to DX Studio which were used to represent the cap lamp, refuge chamber lights, and mining vehicle lights, as well as a configurable level of ambient light. Two spotlight objects were used to model the focussed beam and associated spill of the cap lamp. These spotlights were subsequently attached to the primary camera such that the cap lamp light would orientate its beam in relation to the user's viewing perspective. Point lights, which provide equal amounts of light in all directions, were used to represent the red and green refuge chamber lights. These lights were made to flash in a manner consistent with their real world counterparts via script by turning each light on and off periodically. Revolving spotlights were attached to the roofs of four wheel drive vehicle models in order to represent the hazard lights that are present on all mining vehicles within the Challenger mine. Figures 5.11, 5.12, and 5.13 depict cap lamp, refuge chamber, and mining vehicle lights within the virtual mine.

Figure 5.11. Cap lamp light within the virtual mine
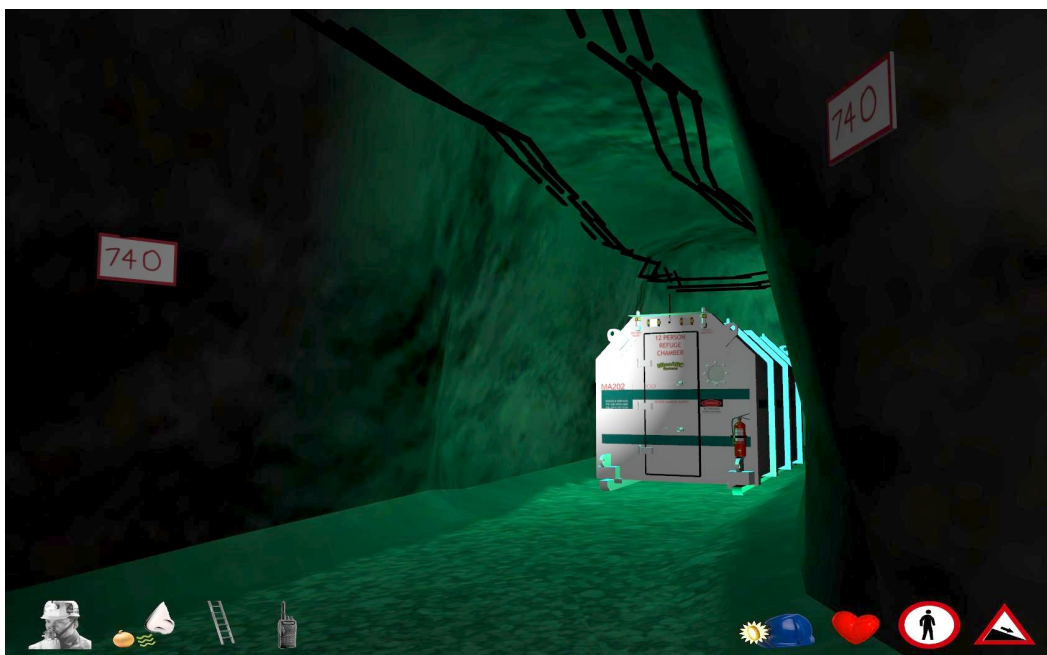
Figure 5.12. Flashing refuge chamber lights within the virtual mine

Figure 5.13. Mining vehicle lights within the virtual mine

Real time shadows were enabled for the player model, mining vehicles, escape rise ladders, and refuge chambers such that they would be visible when these objects were lit by the cap lamp, refuge chamber lights, or mining vehicle lights.

5.2.1.7 Fire and Smoke

The vehicle fire and resultant smoke within the virtual mine were simulated using 2D animated sprites in conjunction with exponential fog rendered by the DX Studio engine. The fire and smoke sprites were positioned in close proximity to a mining vehicle model in order to simulate a vehicle fire, with fog being used to represent the spread of the smoke throughout the mine. The intensity of the fog was determined according to the user's distance from the fire such that the smoke appeared to intensify as they got closer to it's origin. The smoke was also made to appear as though it was propagating throughout the mine by increasing the variable which represented the distance at which the fog would begin to be rendered over time. Figures 5.14 and 5.15 depict a vehicle fire and the simulated smoke represented by fog in DX Studio respectively.

Figure 5.14. Vehicle fire within the virtual mining environment

Figure 5.15. Simulated smoke within the virtual mine environment

5.2.1.8 User Interaction

As detailed in Chapters 4.2.7 and 4.3.6, the simulation environment was required to respond immediately to user activity in order to support the user's sense of presence within the virtual mine. The simulation environment was thus required to exhibit no noticeable lag or delay during rendering, maintaining a frame rate equal to or better than twenty frames per second. To this end, the number of polygons in each 3D model were kept as low as possible and texture resolutions were limited to 1024x1024 for sections of the mine shaft and 256x256 for everything else such that the demand on the system could be minimised and performance maintained. A variable was used to monitor the number of times the frames per second dropped below thirty, with results indicating that the system was not overburdened.

The scripting functionality of DX Studio was used to provide immediate system response to user input in order to approximate real world interaction. An animated player model was used as an avatar for the user, with the camera attached to the head of the model and configured via script to orientate the viewing perspective in response to mouse input. Keyboard inputs were also associated via script with movement forwards, backwards, left, and right in addition to equipping the user's self rescuer, changing the beam setting on their cap lamp, climbing an escape rise, and toggling between walking and running.

Movement speeds were approximated according to information provided by Subject Matter Experts at Challenger at 5km an hour and 10 km an hour for walking and running on level terrain respectively. Approximate times for walking and running both up and down the decline were also provided, but these values were determined to be little different to those for level terrain owing to the gradual slope of the decline. Thus, the values for walking or running throughout the virtual mine were set to 1.39 and 2.78 metres per second respectively. However, during testing these values were found to be too slow to traverse the large expanse of the virtual mine, thus walking and running speeds were increased slightly to 2 and 4 metres per second respectively.

5.2.1.9 Physical Exertion

The physical exertion of the user was evaluated via script according to the speed at which they were moving and the inclination of the terrain they were moving over in the virtual mine.

Information supplied by Subject Matter Experts at Challenger was used to determine a series of possible values for the user's physical exertion for this purpose, as detailed in Table 5.4. Climbing an escape rise was deemed to be the most physically demanding activity, whilst remaining stationary was deemed to be the least demanding.

Table 5.4. Values for physical exertion based on user interaction in order of increasing value

Value	Criteria
0	User not moving
1	User walking over level terrain
2	User running over level terrain
3	User walking down the decline
4	User running down the decline
5	User walking up the decline
6	User running up the decline
7	User climbing an escape rise

5.2.1.10 Self-rescuer Oxygen Consumption

The value of the physical exertion variable was used to determine the rate at which the oxygen capacity of the user's self-rescuer was depleted when activated. Using data supplied by Dominion which outlined the approximate duration of oxygen supply for the self rescuer in relation to physical activity (see Table 4.3), a depletion rate for the oxygen in a self-rescuer in FUMES was established, as detailed in Table 5.5:

Table 5.5. Self-rescuer depletion rate within the virtual mine

Activity	Duration of Oxygen Supply	Depletion rate per second	Value of the Physical Exertion Variable
Stationary	~ 100 minutes	0.0167% per second	0
Walking	~ 30 minutes	0.055% per second	1
Level running	~ 10 minutes	0.167% per second	2
Climbing an escape rise	~ 10 minutes	0.167% per second	9

Using these depletion rates as a basis, additional rates were extrapolated for the remaining

values of physical exertion based on the following information provided by Subject Matter
Experts at Challenger:

- Walking or running down the decline required less effort than walking or running across
  level terrain;
- Walking or running up the decline required more effort than walking or running across
  level terrain, and;
- Climbing an escape rise required the greatest amount of physical effort;

Table 5.6 outlines the extrapolated self-rescuer depletion rates based on the information
provided by Subject Matter Experts at Challenger. These were integrated into a script in DX
Studio in order to deplete the user's self-rescuer by the appropriate amount each second
according to the physical activity they were undertaking within the virtual mine.

Table 5.6. Self-rescuer depletion rates based on the value of the user's physical exertion

Physical Exertion	Criteria	Depletion rate per second
0	Stationary	0.0167% per second
3	Walking down decline	0.047% per second
1	Level walking	0.055% per second
5	Walking up decline	0.075% per second
4	Running down decline	0.138% per second
2	Level running	0.167% per second
6	Running up decline	0.28% per second
7	Climbing escape rise	0.33% per second

5.2.1.11 Cap-lamp Battery Consumption

Cap lamp battery consumption was calculated according to information supplied by Subject
Matter Experts at Challenger as detailed in Table 5.7. The cap lamp battery capacity was
depleted via a script which was called each second according to the current beam setting.

Table 5.7. Cap lamp battery consumption

Cap lamp beam setting	Duration of battery life	Depletion rate per second
Low	~ 1800 minutes	0.0092%
High	~ 900 minutes	0.0018%

5.2.2 Integration of the Problem-solving Task

The problem-solving task was integrated into FUMES using visual and auditory prompts, scripting functionality, and collision detection triggers within DX Studio. These mechanisms were used to present the user with a problem which was consistent with emergency evacuation scenarios at Challenger in order to elicit existing knowledge towards resolution and develop new knowledge which could be transferred and utilised in the real world.

The contextual details of the problem-solving task were clearly identified for users using a series of briefing screens which were presented prior to undertaking problem-solving activity in the virtual mine. This was followed by the exposition of the problem statement using auditory declarations in order to represent the emergency radio broadcast system used at Challenger to initiate evacuations. The conditions of each problem-solving instance were designated using three separate scene files in DX Studio in which the user's starting location, environmental conditions within the virtual mine, and possible problem outcomes were specified and evaluated.

5.2.2.1 Establishing the Context

Prior to beginning problem-solving activity, FUMES presented users with an initial briefing in order to clearly establish the context of the problem and provide information necessary to achieving resolution. These briefing screens established the goals and key aspects of the problem-solving task as well as the means of interaction available to the user within the simulation environment. This information was divided into a series of five briefing screens which were presented in sequential order and provided:

- An introductory overview of the problem-solving activity and notification of assessment in accordance with Dominion's procedures for emergency evacuation at Challenger (Figure 5.16);
- An overview of the keyboard and mouse controls for movement and orientation

respectively (Figure 5.17);

- An overview of the keyboard controls for activating the self rescuer and cap lamp and climbing escape rises (Figure 5.18);

- An overview of the graphical icon feedback mechanisms used by the simulation environment, the application of which is detailed in Chapter 5.2.3 (Figure 5.19), and;

- A list of key aspects to consider with regard to the problem-solving task and a re-statement of its primary objective (Figure 5.20).
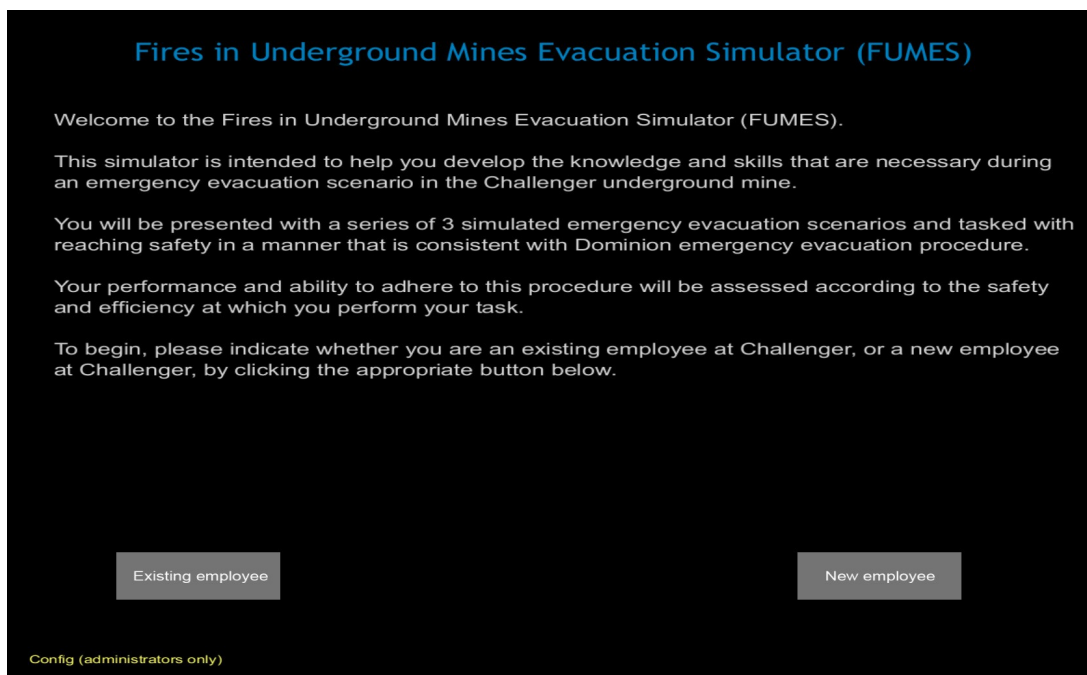
Figure 5.16. First briefing screen
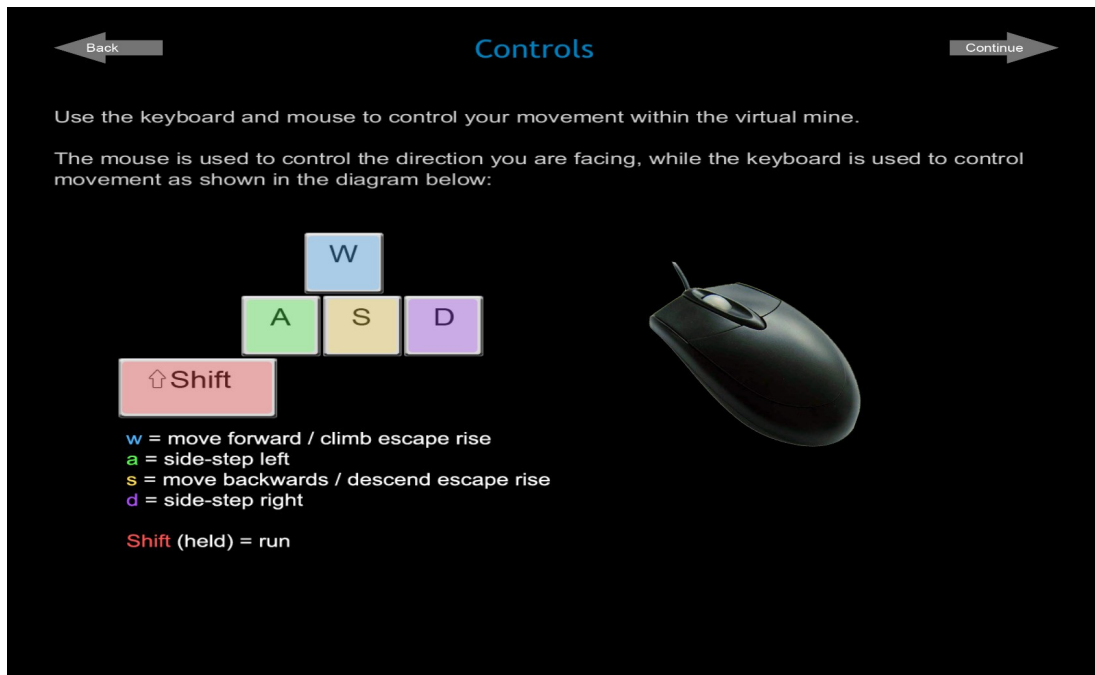
Figure 5.17. Second briefing screen
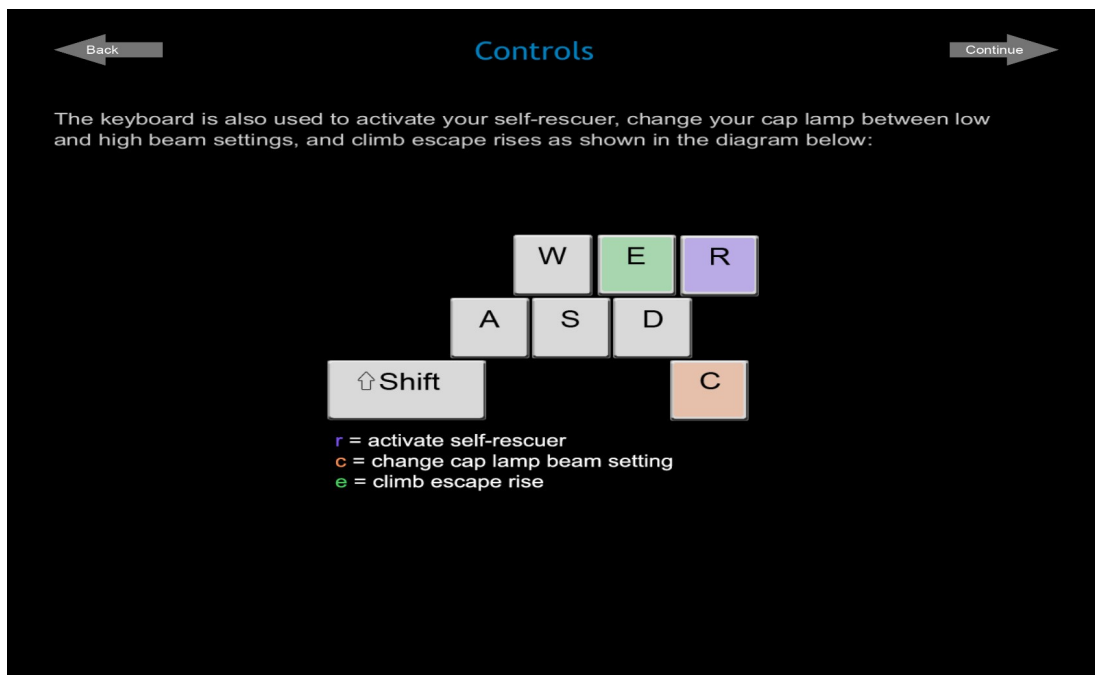
Figure 5.18. Third briefing screen
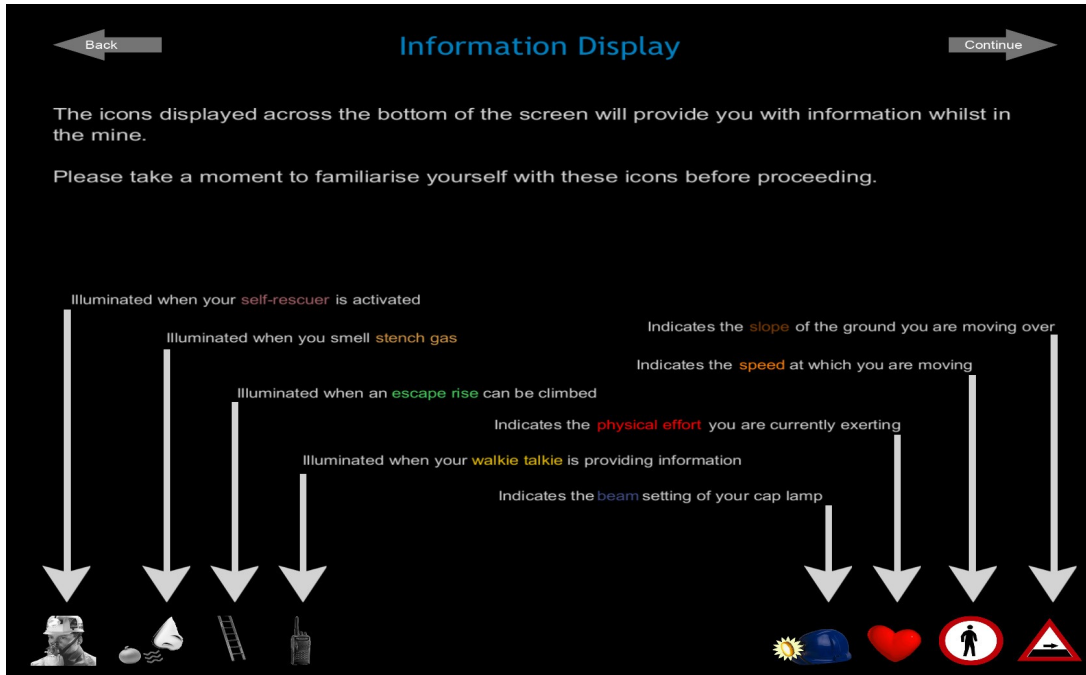
Figure 5.19. Fourth briefing screen
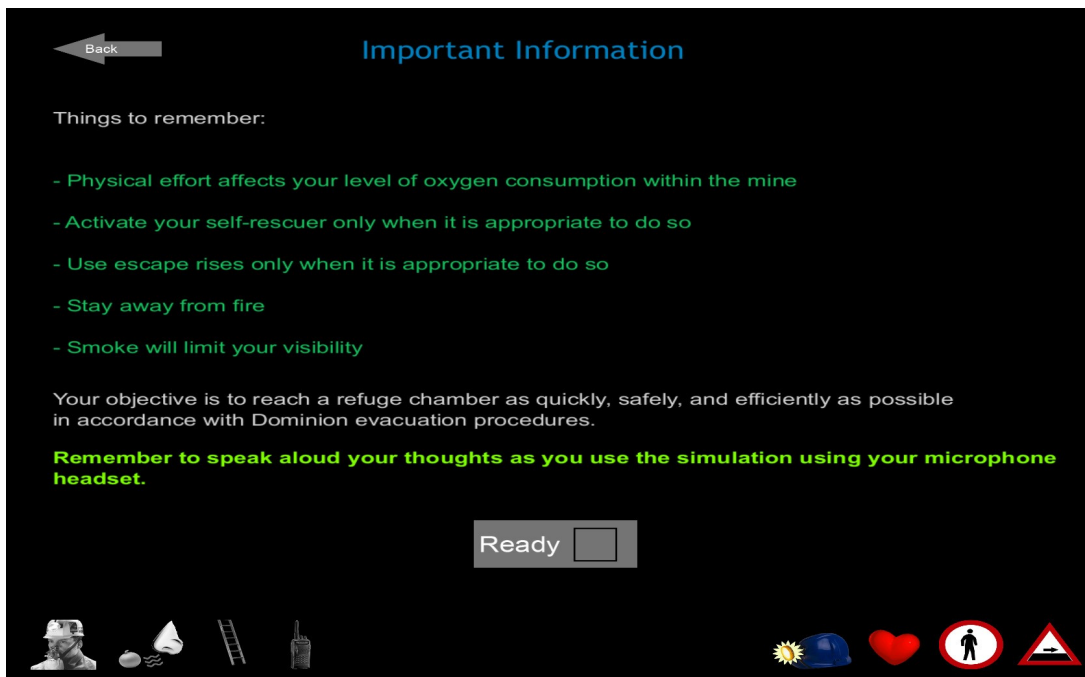
Figure 5.20. Fifth briefing screen

5.2.2.2 Statement of the Problem

Auditory cues were employed within DX Studio to state the problem in a manner that was authentic and appealed to users existing knowledge of emergency evacuations in the Challenger mining environment. Recorded vocal statements ordering an evacuation were employed for this purpose to approximate the emergency broadcast system used at the Challenger mine. This audio was processed in order to sound as though it was being received by a personal radio by removing the lower frequency ranges and applying distortion. In keeping with the problem design established in Chapter 4, each successive problem-solving instance provided less problem structure in turn in order to encourage the user to assume increasing control of the learning process. The information provided by these auditory cues for each problem-solving instance is detailed in Table 5.8

Table 5.8. Statement of the problem using auditory cues

Problem-solving Instance	Contents of audio recording problem statement
1	"This is an emergency. There is a report of smoke on level 960. All personnel must retreat immediately to the nearest refuge chamber. You are on the decline on level 760. The closest refuge chambers are on levels 740 and 860."
2	"This is an emergency. There is a report of a vehicle fire on level 780. All personnel must retreat immediately to the nearest refuge chamber."
3	"This is an emergency. There is a report of smoke throughout the mine. All personnel must retreat immediately to the nearest refuge chamber."

5.2.2.3 Specification of Problem Conditions

The individual characteristics of each problem-solving instance were specified via three independent scene files in DX Studio. Each scene file contained scripts which designated the user's initial location, the location of the vehicle fire, and the severity and rate at which smoke spread through the virtual mine at the onset of each problem-solving instance. In this manner, the user was exposed to a variety of emergency evacuation scenarios within the virtual mining environment that required them to make decisions in response to the circumstances thrust upon them. Furthermore, each successive problem-solving instance placed greater demands on the

user by virtue of the increased complexity and domain specificity involved in successfully charting a route to refuge, as summarised in Table 5.9. This also served as mechanism for slowly seeding control of the learning process to the user by virtue of increased responsibility for safely negotiating the environmental hazards within the virtual mine.

Table 5.9. Conditions for each problem-solving instance

Problem-solving instance	User's starting position	Smoke and fire	Problem outcomes
1	Level 760 decline	Not accessible to the user	1) User successfully reaches a refuge chamber
2	Level 780 side shaft. The decline and vehicle fire are visible from the user's starting location.	A vehicle fire is blocking the user's access to the decline on Level 780, forcing them to use an escape rise to clear the blockage and reach refuge. Smoke is confined to an area close to the fire and is spreading slowly.	1) User successfully reaches a refuge chamber 2) User fails due to contact with fire 3) User fails due to being exposed to smoke for a period greater than 30 seconds without a functioning self-rescuer equipped
3	Level 820 side shaft. The decline is visible from the user's starting location.	A vehicle fire is blocking the decline between Level 800 and Level 780, requiring the user to use an escape rise to clear the blockage or evacuate to the refuge chamber at Level 860. Smoke is prevalent throughout large sections of the mine, including locations very close to the user's starting position, and is spreading quickly.	1) User successfully reaches a refuge chamber 2) User fails due to contact with fire 3) User fails due to being exposed to smoke for a period greater than 30 seconds without a functioning self-rescuer equipped

The problem outcomes detailed in Table 5.9 were evaluated using scripting and collision detection mechanisms within DX Studio. Triggers for detecting collisions with the user were attached to the refuge chamber, vehicle fire, and smoke assets within the virtual mine such that the outcome of the problem-solving task could be determined via a corresponding script based on user interaction.

5.2.3 Guiding Learning

Mechanisms used to guide the learning process were integrated into FUMES using a combination of DX Studios scripting interfaces, collision detection triggers, and visual and auditory prompts. These instructional devices were used to manoeuvre the user towards problem resolution and facilitate the development of knowledge and skills that would be applicable during a real world emergency evacuation of the Challenger mine.

The virtual mining environment provided information for users in their attempts to safely reach refuge and resolve the problem-solving task. Users assumed responsibility for the acquisition and application of visual and auditory information to maintain spatial and situational awareness as they moved and orientated themselves within the virtual mine (Chapter 5.2.1). This provided users with a degree of control over the learning process which was slowly increased with each successive problem-solving instance. This was realised by decreasing the amount of information provided in the problem statement and increasing the severity of the environmental conditions which acted as barriers to resolution for each successive problem-solving instance (Chapters 5.2.2.2 and 5.2.2.3).

Additional scripting constructs were employed within DX Studio to facilitate problem resolution through the implementation of a facilitator like construct which was used to monitor user behaviour in order to determine when to administer feedback. This was supplemented via scripting interfaces which monitored and evaluated key user characteristics to provide an assessment of their performance at the conclusion of each problem-solving instance. The outcome of each problem-solving instance also served as the impetus for explicit prompts for reflection, which were presented to the user to encourage introspective evaluation of their performance.

5.2.3.1 Facilitating Problem Resolution

A facilitator like construct was implemented using scripted responses to user behaviour in DX Studio to support them as they undertook problem-solving activity. The facilitator construct provided auditory responses under the guise of personal radio communications within the virtual mine in order to appeal to users existing experience with emergency evacuation scenarios at Challenger. Collision detection triggers in DX Studio were used by the facilitator construct as

the impetus for auditory responses, the contents of which are detailed in Table 5.10.

Table 5.10. Contents of auditory responses provided by the facilitator construct

User action	Response provided by the facilitator construct	Contents of audio response
User heading in the wrong direction	Asks the learner if they are sure they are heading in the right direction	"Are you sure you're headed in the right direction?"
User continues to head in the wrong direction	Tells the learner that they are headed in the wrong direction and to turn around immediately	"You're going the wrong way. The closest refuge chamber is not in this direction. Turn around."
User encounters smoke	Asks the learner what they should do when they first encounter smoke	"What should you do when you encounter smoke?"
User encounters smoke and is in danger of dying because they have not equipped their self-rescuer	Tells the learner to equip their self-rescuer immediately or they will succumb to the smoke	"Equip your self rescuer now or you are going to succumb to the smoke."
User getting too close to a vehicle fire	Tells the learner that they are getting too close to the fire	"You're getting too close to the fire."
Use of escape rise	Asks the learner whether it was necessary to use the escape rise	"Was it necessary to use the escape rise?"
Remaining self-rescuer capacity	Tells the learner when their self-rescuer gets to 50%, 10%, and 0% oxygen capacity respectively	"Your self rescuer is now at 50% oxygen capacity." "Your self rescuer is now at 10% oxygen capacity. You must find refuge soon." "You have exhausted your self rescuer. Get to a refuge chamber or area with sufficient breathable oxygen now!"
Interruption of external oxygen and power supplies	Tells the learner that external supplies of oxygen and power have been interrupted	"The air and power supplied from the surface has been interrupted as a result of the fire."

Feedback provided at the task environment level was implemented using a combination of graphical, textual, and auditory based responses. Graphical icons were positioned along the bottom of the screen to provide feedback relating to the user's movement and physical exertion as they traversed the terrain of the virtual mine, their proximity to stench gas, their application of the cap lamp, self-rescuer, and escape rises, and the provision of information under the guise of personal radio communications, as outlined in Table 5.11. Figure 5.21 details a corresponding screen shot of these graphical icons as depicted in FUMES.

Table 5.11. Application of graphical icons for task environment feedback

Type of information	Description	Icon
Self rescuer activation status	Learner has activated the self rescuer	Image depicting a man wearing a self rescuer which appears in colour if the self rescuer has been equipped and grey scale otherwise
Stench gas detected	The user has detected the smell of the stench gas system	Image depicting a nose smelling an onion which appears in colour when stench gas has been detected and grey scale otherwise
Escape rise status	The user is close enough to an escape rise to climb it	Image depicting a ladder which appears in colour when the user is close enough to an escape rise to climb it and grey scale otherwise
Personal radio communication	Informs the learner when their personal radio is being used to provide information	Image depicting a personal radio which appears in colour when a radio communication is being received and grey scale otherwise
Cap lamp status	User changes the cap lamp beam setting between low and high	Image depicting a helmet with a cap lamp. The area illuminated around the cap lamp is shown to extend further when high beam is used.
Physical exertion	Level of physical activity required to traverse the virtual environment dependent on the inclination of the terrain and the user's movement speed	Animated heart which is shown to beat slowly when the user is stationary or walking and quickly when the user is running or climbing an escape rise
Movement speed	Feedback to represent footsteps within the virtual mine that is provided in response to the user's movement speed and the terrain that they are traversing	Image depicting a person within a white circle with a red border which is shown to be stationary, walking, or running depending on the user's movement speed.
Terrain inclination	Informs the user as to the current slope of the terrain	Image depicting a plane with an arrow which is shown to be level, uphill, or downhill depending on the inclination of the terrain over which the user is moving.

Figure 5.21. Graphical icons used to provide feedback

The feedback provided by the task environment detailed in Table 5.11 and Figure 5.21 was further supplemented via the application of auditory cues. The same script used to set the status

of the graphical icons within DX Studio also assumed responsibility for initiating the playback of supporting audio such that both forms of feedback were provided simultaneously in order to compliment each other. Auditory cues representing footsteps in the mine, breathing, climbing an escape rise, and exposure to smoke and fire were utilised to this end, as summarised in Table 5.12.

Table 5.12. Auditory responses used to provide feedback in the task environment

Type of information	Audio
Movement speed	· Walking and running on gravel respectively
Physical exertion	· Breathing , the rate of which corresponds to the extent of physical exertion · Heart beat, the rate of which corresponds to the extent of physical exertion
Self rescuer activation status	· Breathing through a oxygen mask, the rate of which corresponds to the extent of physical exertion
Oxygen supply in self rescuer depleted	· Asphyxiation if in area of the mine in which smoke is present
Escape rise status	· Metal ladder rungs being climbed
Exposure to smoke	· Coughing if self rescuer not equipped or depleted · Gasp (indicating death) after extended exposure without a functioning self rescuer
Exposure to fire	· Painful scream (indicating death)

Text based responses were also displayed in the top centre region of the screen to further supplement the information provided by the graphical icons and accompanying auditory cues. Table 5.13 details this information accordingly, with Figure 5.22 depicting a screen shot of this text based feedback in FUMES.

Table 5.13. Text based responses used to provide feedback in the task environment

Type of information	Text
Self rescuer activation status	Timer counting down from thirty seconds which details the time remaining before the self rescuer is active Text informing the user as to the remaining self rescuer capacity when capacity is at 50%, 10%, and 0% respectively
Escape rise status	Text informing the user that they cannot climb an escape rise when an attempt to climb is made whilst equipping a self rescuer.
Stench gas detected	Text informing the user that they have detected the odour of rotten onions when the stench gas system has been activated.
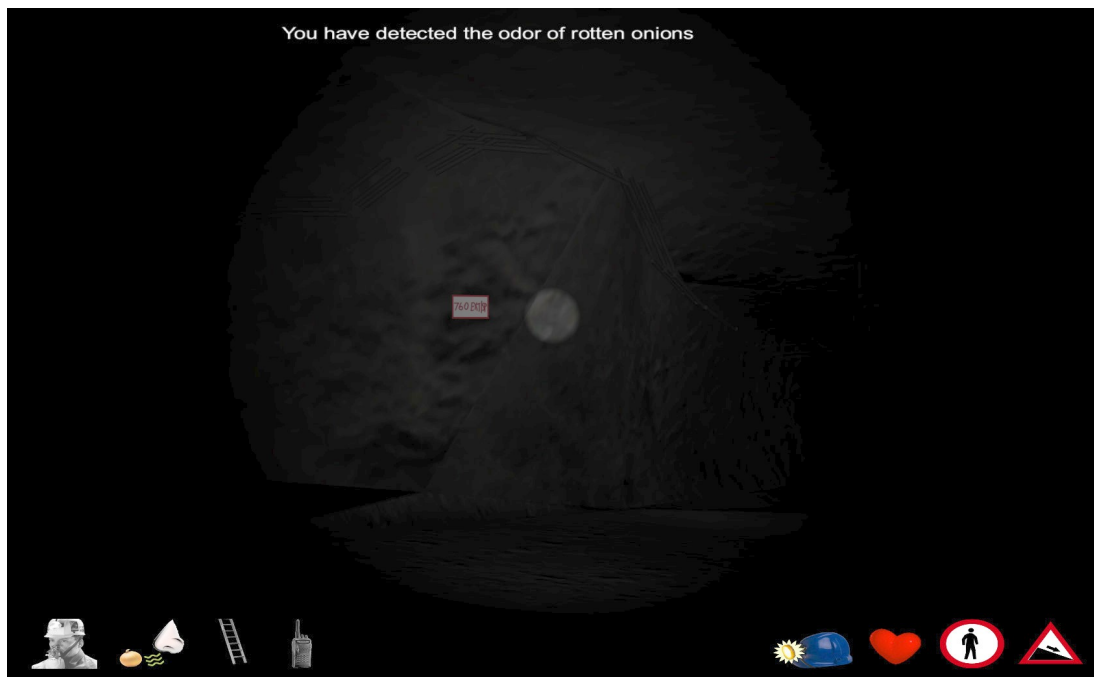
Figure 5.22. Text displayed in the top centre of the screen to supplement graphical icon and auditory feedback

5.2.3.2 Assessment of User Performance

Assessment measures were calculated using variables to measure key aspects of the user's performance. These were initialised at the onset of each problem-solving instance and in turn displayed to the user at its conclusion. Table 5.14 outlines the measures of user performance integrated within the simulation and the manner in which their values were calculated. Figure 5.23 depicts the manner in which these assessment measures were formatted and displayed to the user at the conclusion of each problem-solving instance.

Table 5.14. Assessment measures implemented to evaluate user performance

Assessment measure	Measurement	Textual feedback provided
Outcome of the problem-solving instance	Determined to be a success if the user makes physical contact with an area in close proximity to a refuge chamber. Determined to be a failure if the user makes physical contact with an area in close proximity to a vehicle fire. Determined to be a failure if exposure to an area affected by smoke exceeds a 30	User informed as to the outcome of the problem-solving instance

	second timer event.	
Elapsed time	Simple timer which is initialised at the onset of each problem-solving instance and stopped once an outcome has been reached	Time taken in minutes and seconds.
Physical exertion	Calculated according to the average extent of physical exertion throughout the problem-solving instance. Deemed to be low if the user walked predominantly, moderate if ran at some points or used escape rises, and high if they ran extensively or climbed numerous escape rises.	Approximated physical effort expended (low, moderate, or high)
Distance travelled	Incremented according to the user's movements throughout the mine and the speed at which they move.	Total distance travelled by the user in metres
Remaining self-rescuer capacity	Utilises the value of the corresponding variable	Remaining self-rescuer capacity as a percentage
Remaining cap lamp capacity	Utilises the value of the corresponding variable	Remaining cap lamp capacity as a percentage
Ideal refuge chamber	The ideal refuge chamber for a given problem-solving instance is that which requires the least amount of physical effort to reach	User informed as to whether the refuge chamber they selected was ideal given their starting position and the environmental conditions within the mine. If the user has failed to reach a refuge chamber they will be informed accordingly.
Ideal route	The sequence of sections of the terrain that needed to be traversed to reach each refuge chamber were compared against the sequence of sections traversed by the user for each problem-solving instance.	User informed as to whether they took the most efficient route to the refuge chamber they selected. If the user has failed to reach a refuge chamber they will be informed accordingly.
Escape rise usage	The escape rises that could be climbed in order to clear a blockage were compared to those actually climbed by the user for each problem-solving instance	User informed as to whether their escape rise usage was necessary and appropriate
Self-rescuer usage	Determined to be necessary if the user has traversed an area of the mine in which smoke is present.	User informed as to whether their self rescuer usage was necessary and appropriate
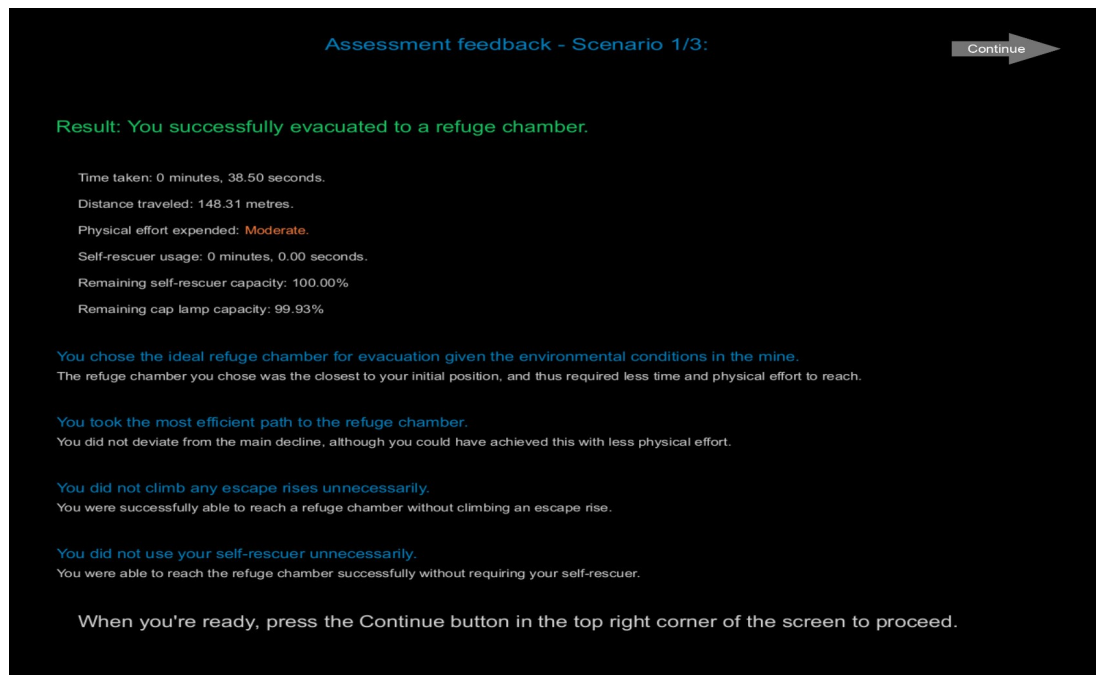
Figure 5.23. Assessment feedback provided to the user

5.2.3.3 Explicit Prompts for Reflection

Explicit reflection prompts were displayed to the user following the provision of assessment feedback. Simple on screen text was employed for this purpose, the contents of which depended on the outcome of the problem-solving instance. In this manner, the user was prompted to reflect on their performance based on whether they successfully evacuated to refuge, or failed due to exposure to smoke or fire within the virtual mine, an example of which is depicted in Figure 5.24.
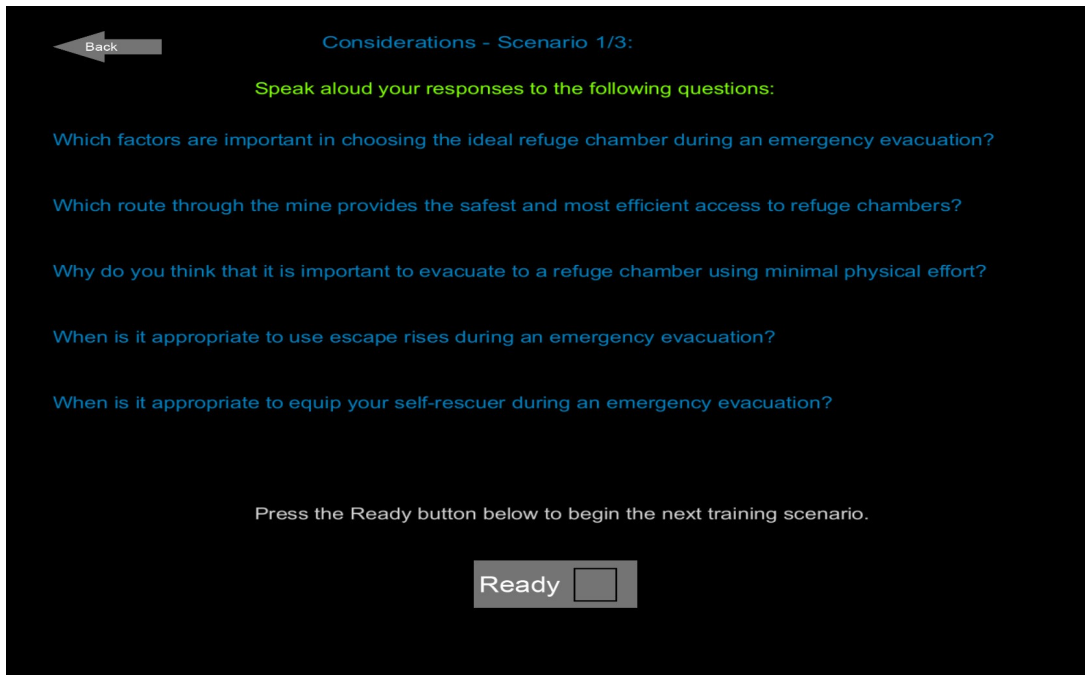
Figure 5.24. Reflective prompts presented to the user

5.2.4 Known Limitations in the Implementation of the Design

A number of limitations in the implementation of the design were identified throughout the development process. These limitations arose due to a lack of experience with the development platform in addition to the limited time frame that was allocated for development. The potential impact of these limitations are detailed in Table 5.15.

Table 5.15. Known limitations in the implementation of the design

Limitation	Details	Potential impact
Modelling of smoke	Spread of smoke within the Challenger mine not accurately modelled	User unlikely to gain an awareness as to how smoke behaves within the Challenger mine during an underground fire
Movement speed	Walking and running speeds increased in relation to those possible within the real world environment	User may gain a false impression as to how quickly they can travel within the real world mine. May affect the user's ability to judge distances between areas of the mine
Modelling of physical exertion	Simplified model based on ranking and interpolation of physical activities according to effort expended within the	User unlikely to be able to gain an appreciation as to how much physical effort would be required to perform corresponding actions within the Challenger mine. However, the

	virtual mining environment	simulation does provide an indication as to physical activities that are demanding, and those that aren't
Modelling of mining infrastructure	Jumbo boxes and other mining infrastructure such as vent bags were not depicted within the virtual mining environment	Less visual cues available for way-finding and navigation. Virtual mine less authentic
Modelling of self rescuer oxygen consumption	Simplified model based on information supplied by Dominion indicating duration of supply for low, moderate, and high physical activity	Simulation does not accurately model the depletion of self rescuer oxygen, but does indicate the affect that physical exertion has on the duration of supply
Depiction of escape rise interaction	Simulation does not depict the climbing of escape rises from a first person perspective. This depiction is also sped up so that it takes less time than it does in the real world.	Decreased sense of presence and immersion Reduced appreciation of the time taken to climb an escape rise, although the actual time taken is stated explicitly (see Figure 5.6)
Modelling of the Challenger mine	The virtual mining environment only portrayed a small section of the Challenger mine with access restricted to some sub-shafts that lead away from the main decline.	Activity not situated within a complete virtual representation of the Challenger mine User will be unable to develop any spatial knowledge of the Challenger mine outside of the area that has been modelled and is accessible
Visual detail in virtual mining environment	The level of visual detail in the virtual mine was low overall due to the sheer scale of the real world mining environment.	Virtual mine less authentic Difficulty in maintaining locational awareness due to uniformity of the environment

The impact of these limitations on participant experience with FUMES during the study is explored in Chapters 6 and 7.

5.3 Evaluation of DX Studio

A post-development evaluation of the DX Studio platform was conducted in relation to the game engine selection criteria established in Table 5.1. This evaluation identified a number of strengths and weaknesses of DX Studio that were not immediately evident during the initial evaluation of the trial version of the software.

5.3.1 Development Suite

The DX Studio development suite provided an effective means by which to separate two-dimensional and three-dimensional assets via the use of a hierarchy of configurable layers. Two-

dimensional graphical and textual content used for on-screen text and icons was collated in a two-dimensional layer for this purpose. Likewise, the content used to represent the virtual mining environment was collated in a single three-dimensional layer within the DX Studio development suite. This configuration allowed associated groups of content to be easily and efficiently acted upon via scripted events. Figures 5.25 and 5.26 depict the development of a two-dimensional and three-dimensional layer within DX Studio respectively.
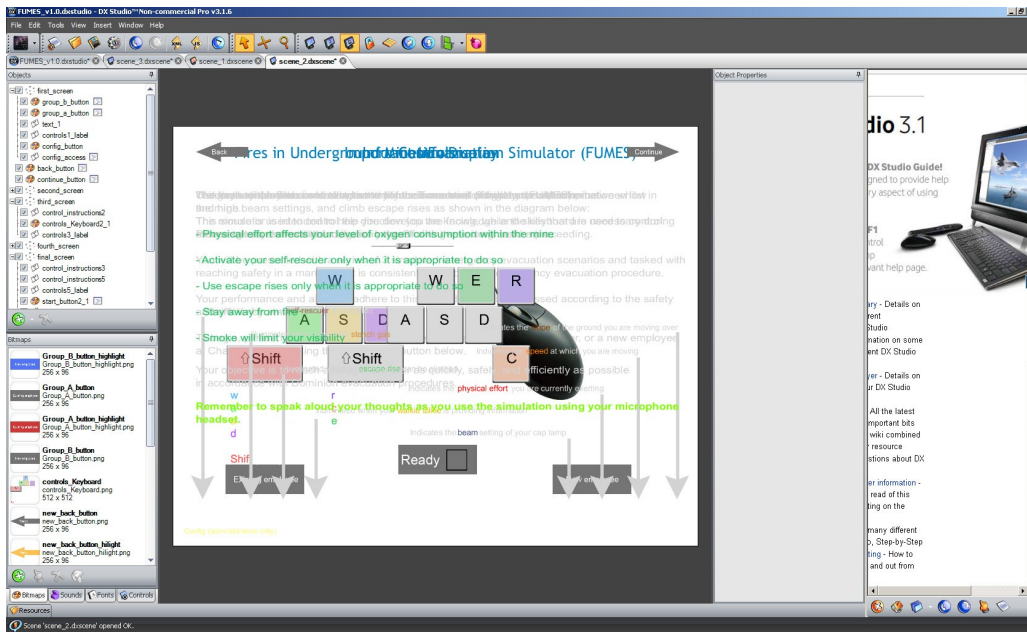
Figure 5.25. Two-dimensional layer within DX Studio development suite
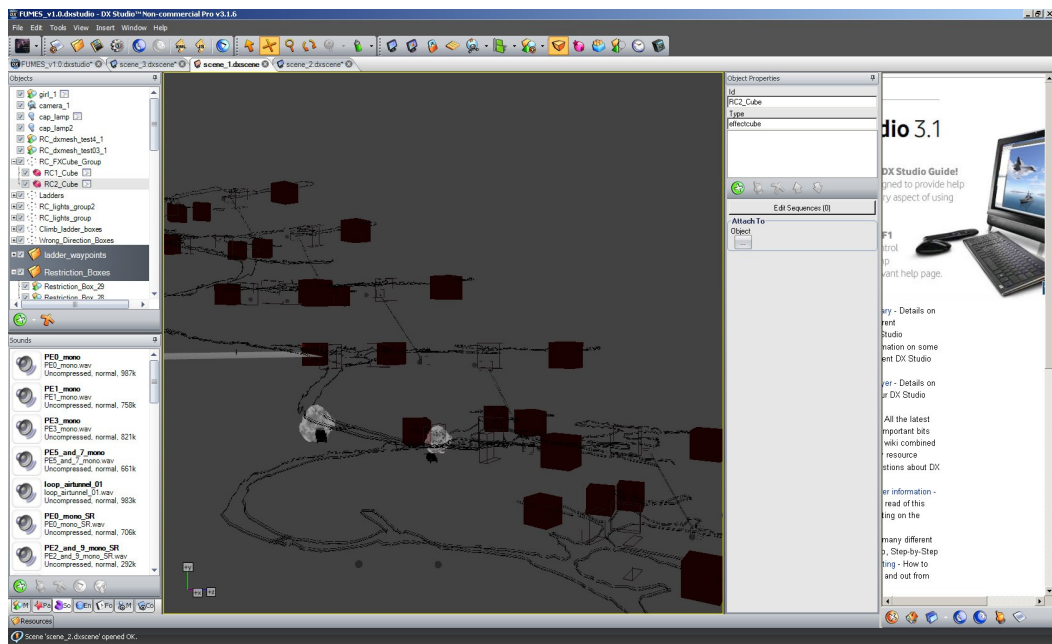
Figure 5.26. Three-dimensional layer within DX Studio development suite

The 2D layer interface within DX Studio allowed graphical and textual content to be positioned where it would appear on-screen. Positioning content within the 3D layer was not quite as exacting however, as the interface only provided a solitary view of the 3D environment making precise placement difficult. Multiple view ports or the presence of a larger grid overlay may have allowed for greater precision and served to alleviate this issue.

The 3D layer interface also provided a number of useful tools which were used during the development of FUMES. The material editor allowed various texture maps and material channels to be specified and configured with ease, as depicted in Figure 5.27. Similarly, the texture paint feature included in DX Studio provided a quick and easy way to add textural detail to the floors of the virtual mine.
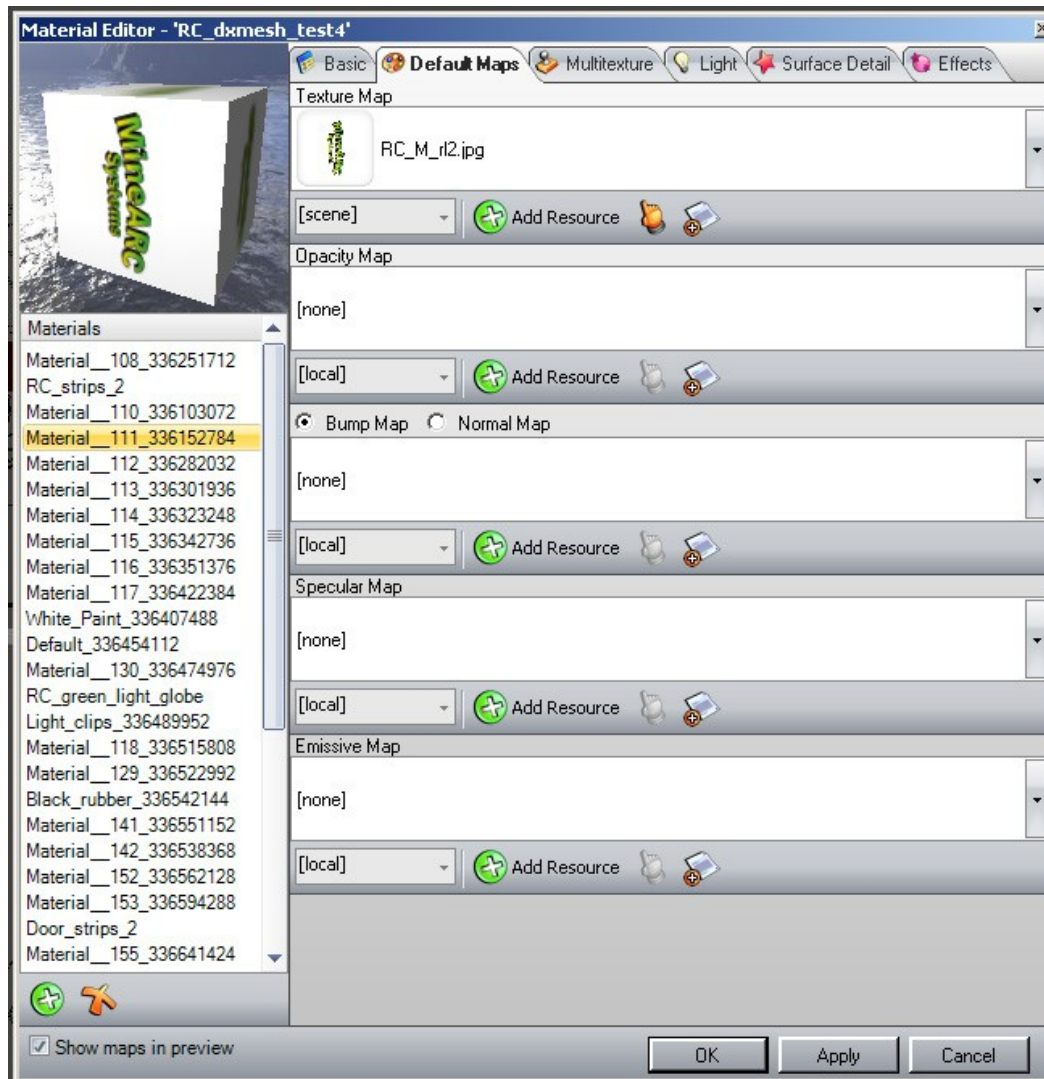
Figure 5.27. Material editor in DX Studio

5.3.2 Scripting Capabilities

Scripting functionality was implemented using Javascript in DX Studio. All objects and layers created during development could have scripts attached to them, and this was used to associate events and responses with specific assets such as the user model, refuge chambers, and cap lamp. Layer and document level scripts were also used to establish the instructional sequences required to represent each problem-solving instance within FUMES.

The scripting capabilities of DX Studio also provided access to a library of functions. This library was populated by a collection of events which could be called in response to certain conditions within the simulation environment. Events for common functions such as physical

contact between objects, notification of specific keyboard and mouse commands, and update functions called every time a new frame was rendered were accessible during scripting and provided an effective means by which to implement core functionality.

While the in-built scripting editor featured syntax checking and a document wide search function, a number of additional features would have improved productivity during development. Context sensitive text formatting, the ability to set break points, and the option to minimise or hide sections of code would have increased work flow and made script management more efficient, especially as the size of the project began to increase.

5.3.3 External Model Support

The dxmesh format made available via an export plug-in for 3DS Max proved to be a reliable means to import model meshes into DX Studio. The structure and composition of models imported into DX Studio were consistent with 3DS Max, where material channels were also properly preserved.

5.3.4 Texture Mapping Capabilities

DX Studio provided support for a wide variety of texture maps including diffuse, bump, normal, specular, opacity, reflection, and emissive, with support for common image formats such as jpg, png, targa, tif, and dds. The majority of 3D meshes depicted within the virtual mine relied on diffuse and normal maps in the png image format, with opacity maps used to depict the steel mesh cages of the escape rises. The ability to set emissive properties for object materials was of particular use in depicting the reflective properties of the surfaces of the signage used to denote escape rises within the mine.

5.3.5 Physics

The physics engine built-in to DX Studio provided an easy way to model the movement of the user avatar within the virtual mining environment. This allowed the 3D model which represented the user's body to move across up and down the decline and pass across the terrain without falling through it. Physics was also enabled for any object that was required to be solid in order to prevent the user from moving through it. Collisions between objects could also be

detected and responded to using the physics engine and corresponding scripted interfaces.

5.3.6 Lighting and Shadows

DX Studios lighting components adequately represented the cap lamp and refuge chamber lights in the virtual mine. Spotlights were used for this purpose and provided enough configurable properties to represent the behaviour of the cap lamp and refuge chamber lights when used in conjunction with a corresponding script.

DX Studio encountered problems lighting some meshes that were not positioned at the origin in 3D Studio Max prior to export, whereby the surfaces of these meshes were not lit properly as shown in Figure 5.28. This created problems for meshes that were situated at the very edge of the virtual mining environment. Attempts were made to quell this problem by increasing the range at which light objects were visible. However, this proved unsuccessful and as a result these meshes had to be centred at the origin in 3DS Max prior to export and then positioned manually within DX Studio, which created visible gaps between some of the meshes.
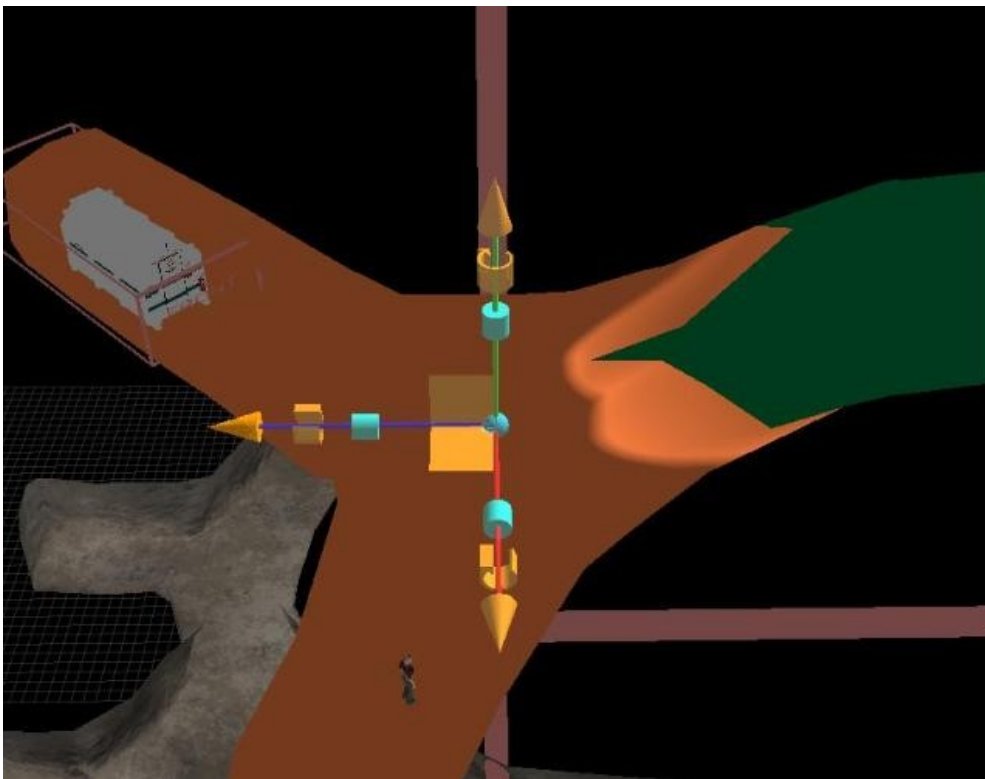
Figure 5.28. Unlit mesh surfaces (green mesh), compared to properly lit mesh surfaces (orange mesh)

5.3.7 Effects

Support for 2D sprites within DX Studio provided an adequate means to represent fire and smoke within the virtual mine, although support for volumetric objects would have increased the authenticity of their depiction, particularly for smoke. Graphics fog was used to decrease user visibility according to their proximity to the fire, with the exponential fog type proving most suitable. The intensity of the graphics fog and rate at which it attenuated was manipulated via script for this purpose.

5.3.8 Audio

The positional audio capabilities of DX Studio provided directional cues for vehicle fires within the virtual mine. The 2D sprite object used to represent the vehicle fire had an auditory asset associated with it, where volume and panning was modified by DX Studio in relation to the user's proximity to the object. In this manner, the user was provided with an indication as to how close and in what direction they were from a vehicle fire.

Other sound effects such as those used for the personal radio, footsteps, and heartbeat were played in a mono configuration as positional information was not required. The properties of all sound samples were accessible via script within DX Studio, and this was used to change which sound sample was being played in accordance with user interaction within the virtual mine. However, DX Studio did not provide an easy way to change the volume of these audio samples inside the development suite, with volume values only able to be changed via script. This made it very difficult and time consuming to balance the audio within FUMES.

5.3.9 Performance and System Requirements

Both the development suite and simulation environment were able to run without any noticeable slowdown or performance problems on a modest desktop PC. However, the development suite had problems with memory management which were a significant handicap throughout the construction of FUMES. These memory issues only affected the development suite and not the compiled simulation environment itself, and only began to occur once the project became larger towards the latter stages of development. Splitting the virtual mining environment into separate

self-contained sections was the only viable way to complete the simulation without the development suite becoming unstable.

5.4 Summary for Developing the 3D Simulation Environment

A number of 3D game engines were considered for the purpose of developing FUMES from the design derived in Chapter 4. The DX Studio platform emerged as the most suitable choice in light of the requirements of the simulation design. An initial evaluation of a trial version of DX Studio indicated that the platform was well suited to rapid development in addition to being cost effective, which was an important consideration given the time and financial constraints imposed by the study.

A physically and functionally authentic representation of an underground fire emergency evacuation scenario in the Challenger mining environment was developed using DX Studio. Spatial characteristics were maintained by using AutoCAD data to construct the virtual mine which was populated with refuge chambers, escape rises, and depth markings as per the real world Challenger mining environment. Smoke and fire was represented using 2D sprites, and the scripting capabilities of DX Studio were utilised to facilitate user interaction and model physical exertion and the functionality of the cap lamp and self-rescuer.

The problem-solving task was integrated into FUMES using scripts and visual and auditory information prompts. A series of text based briefing screens were used to establish the context of problem-solving activity in terms of its goals, key aspects, and mechanisms for user interaction. This was followed by the presentation of the problem statement using auditory cues to replicate the emergency radio broadcast system used at Challenger during evacuations. Three separate DX Studio scene files were used to specify the conditions of each problem-solving instance, whereby the user's starting location, environmental conditions within the virtual mine, and possible problem outcomes were specified and evaluated via embedded scripts.

The user was guided throughout the learning process via the application of scripting interfaces, collision detection triggers, and visual and auditory prompts within DX Studio. Users were able to elicit visual and auditory information from the virtual mining environment to affect safe evacuation to refuge and resolution of the problem-solving task. User control of the learning

process was steadily increased via the implementation of scripts which reduced the information provided explicitly during the problem statement and increased the severity of environmental conditions within the virtual mine with each successive problem-solving instance. Additional scripting constructs were employed to facilitate problem resolution through the implementation of a facilitator like construct which monitored user behaviour and responded with feedback where appropriate. This was supplemented via scripts which evaluated user behaviour to provide an assessment of their performance. Text was also displayed to prompt reflective thinking in relation to the user's performance and the outcome of each problem-solving instance.

A post development evaluation of DX Studio was undertaken after work on FUMES had been completed. This evaluation identified a number of positive attributes of the DX Studio platform, including the accessibility of the development suite, built in physics, texture mapping, and external 3D model support, and the ease at which 2D sprites could be integrated into the simulation. However, a number of technical limitations were also encountered in DX Studio which hampered development and needlessly increased the complexity of the simulation. These were the result of memory management issues and a lack of precision for position assets within the simulation environment.

Having documented the development of FUMES using the DX Studio game engine, Chapter 6 examines the efficacy of FUMES as a training platform for mining personnel at the Challenger mine in order to addresses the first research question proposed by this study. This process was undertaken by analysing the extent to which existing knowledge of emergency evacuations at Challenger was transferred and utilised within FUMES, and the degree to which FUMES developed new knowledge which could be used by mining personnel during a real world emergency.

6 Research Question 1 – Transfer of Learning

The preceding chapter documented the development of a 3D training environment (FUMES) with the DX Studio 3D game engine, using design considerations based on the SUPL Design Framework (Chapter 4), to provide personnel at the Challenger mining facility with a viable emergency evacuation training platform. This chapter evaluates FUMES in terms of its ability to develop knowledge for use during real world emergency evacuations at Challenger in order to address the first research question proposed by this study:

Question 1. To what extent can a problem-based learning environment implemented using 3D gaming technologies promote learning and transfer to real world contexts?

The first research question sought to determine whether problem-solving knowledge and skills could be effectively transferred between virtual and real world environments, and if so, how this could be achieved. This encompassed an evaluation of the effectiveness of FUMES in terms of its ability to facilitate learning transfer.

As detailed in the literature, learning transfer is the primary objective of simulation environments, with success being measured relative to the extent and suitability of the knowledge that has been transferred (A. L. Alexander et al., 2005; McHaney, 1991; Towne, 1995). Such a process is contingent on learning being situated in a simulation environment that accurately reflects the real world environment being modelled and requires contextually relevant instructional support in order to develop knowledge and skills that are transferable (Brown et al., 1989; Dobson et al., 2001; Salomon & Perkins, 1989).

In order to explore how problem-solving knowledge and skills could be transferred between a virtual and corresponding real world environment, the data gathered during the FUMES implementation was analysed for evidence of learning transfer. Questionnaires, interviews, and performance data recorded by FUMES were analysed for this purpose using the two groups of participants drawn from mining personnel at the Challenger mine. The first group consisted of 21 Experienced Participants who had at least six months full time experience at the mine, while the second comprised 20 Novice Participants who were new employees at the mine.

Due to operational issues at the Challenger mine, it was necessary to use methods for measuring learning transfer which did not require performance testing within the real world environment (Tables 3.2 and 3.3). This was necessary as the mine was in operation twenty four hours a day and could not safely or feasibly be used for real world performance testing after participants had completed the problem-solving task within the simulator. The methods employed to measure learning transfer include:

- Chapter 6.1 - Inverse Transfer of Training;
- Chapter 6.2 - Assessment of Fidelity, and;
- Chapter 6.3 - Operator Opinion.

The data collected during the FUMES implementation was examined using each of these methods in order to provide multiple perspectives for evaluating the effectiveness of learning transfer.

6.1 Inverse Transfer of Training

The inverse transfer of training method for measuring learning transfer requires those familiar with a real world operational task to perform the same task without practice in a corresponding simulator (Lathan et al., 2002). A positive result in such a scenario would suggest transfer via the application of existing knowledge.

Positive outcomes for participant performance within FUMES were defined for this purpose based on the metrics used to evaluate how successfully personnel evacuated from the Challenger mine during a real world emergency. These positive outcomes were identified via consultation with Subject Matter Experts at Challenger and are detailed in Table 6.1, as follows:

Table 6.1. Positive outcomes for the evaluation of problem-solving task performance

Positive outcome	Description
Evacuate to refuge chamber	Participant reaches either one of the refuge chambers in the virtual mining environment.
Ideal route	Participant evacuates to a refuge chamber using the ideal route for a given problem-solving instance, emphasising the most efficient route which bypasses fire and smoke where possible.
Ideal refuge	Participant evacuates to the ideal refuge chamber for a given problem-solving

chamber	instance. The ideal refuge chamber is that which can be reached using the least amount of physical exertion and which which bypasses fire and smoke where possible.
Efficiency	Participant traverses the mining environment with an emphasis on taking the least amount of time and travelling the shortest distance possible, whilst also minimising the amount of physical effort expended in order to prolong the oxygen supply in their self-rescuer.
Self-rescuer usage	Participant equips their self-rescuer only when smoke is encountered, with an emphasis on minimising physical exertion in order to maximise the duration of oxygen supply if the self-rescuer is equipped.
Escape rise usage	Participant avoids using escape rises unless they have no other means of circumventing an obstacle which is obstructing access to a refuge chamber.
Encounters with fire and smoke	Participant avoids encounters with smoke and fire where ever possible.

Performance measures (Chapter 6.1.1) and input logs (6.1.2) recorded by FUMES were analysed for evidence of these positive outcomes. The Training Staff Member responsible for the participants on site at Challenger during the study was also interviewed for this purpose (Chapter 6.1.3).

6.1.1 Performance Measures

Measures of problem-solving performance were utilised to determine each participants' effectiveness within FUMES (Chapter 3.3). These performance measures recorded (Table 3.1):

- The outcome of each problem-solving instance;
- How long participants took;
- How far they travelled through the mine,
- How long they used their self-rescuer for;
- What percentage of the self-rescuer oxygen supply they consumed;
- The total amount of physical effort they expended;
- Whether they chose the ideal refuge chamber to evacuate to, and;
- Whether they took the ideal route through the virtual mine to reach it.

These performance measures were analysed for evidence of the positive outcomes established in Table 6.1 regarding evacuation to a refuge chamber, use of the ideal route to reach a refuge chamber, and evacuation to the ideal refuge chamber for a given problem-solving instance. Figures 6.1, 6.2, and 6.3 show participant performance in relation to these three positive outcomes.

Positive Outcome - Evacuate to refuge chamber

number of participants (n) = 41
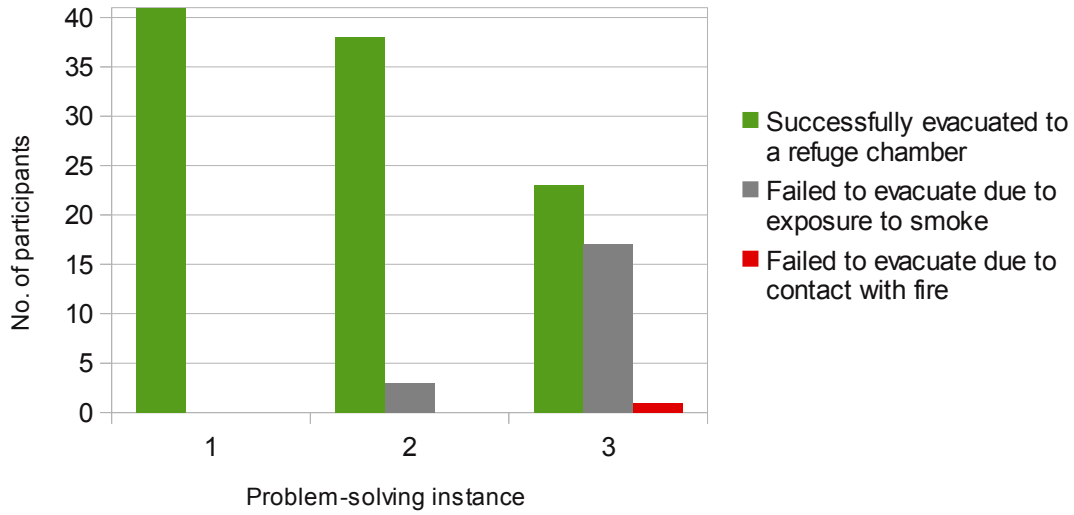
Figure 6.1. Successful evacuation to a refuge chamber

Positive Outcome - Ideal route

number of participants (n) = 41
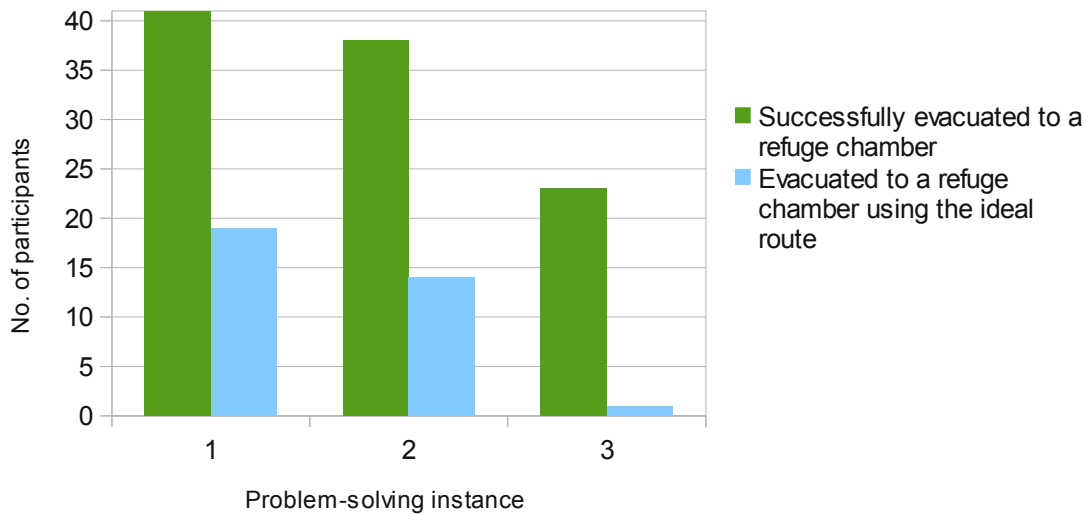
Figure 6.2. Successful evacuation to a refuge chamber using the ideal route

Positive Outcome - Ideal refuge chamber

number of participants (n) = 41
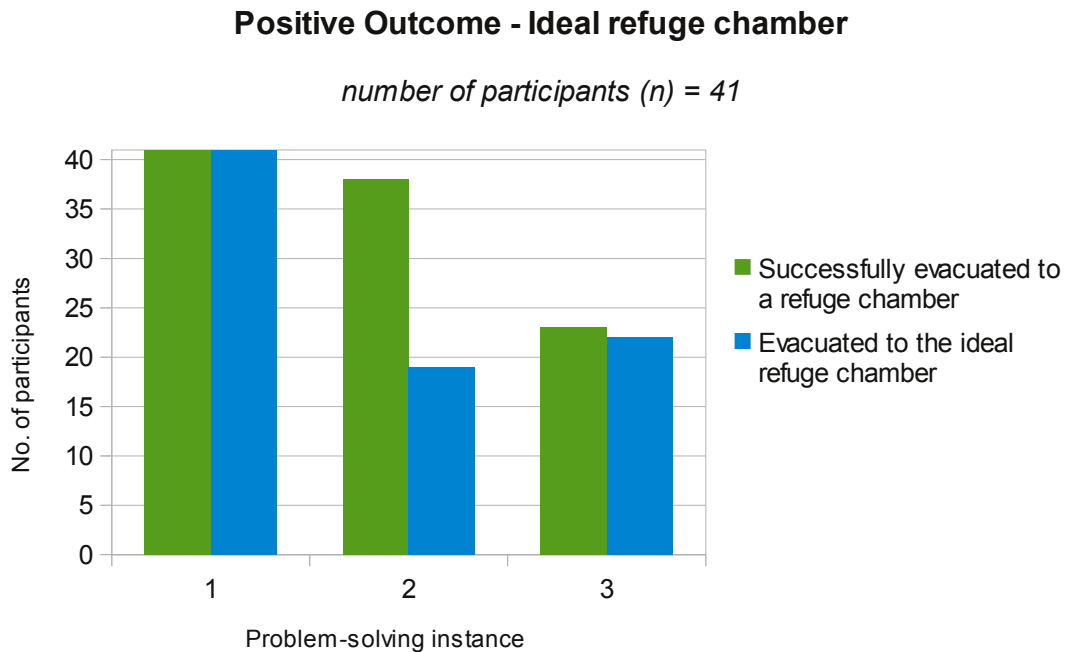
Figure 6.3. *S*uccessful evacuation to the ideal refuge chamber

The performance data depicted in Figures 6.1, 6.2, and 6.3 suggests that participants achieved the following:

- The overwhelming majority of participants were able to evacuate to a refuge chamber in the first and second problem-solving instances. More than half of the participants were able to evacuate to a refuge chamber in the third problem-solving instance, and;
- Nearly all of the participants who successfully evacuated to a refuge chamber in the first and third problem-solving instances evacuated to the ideal refuge chamber.

The first of these performance trends suggests that participants effectively used their existing knowledge of emergency evacuations at Challenger to evacuate to a refuge chamber in the virtual mine, particularly in the first two problem-solving instances. This required participants to recognise a contextual similarity between problem-solving activity in FUMES and emergency evacuation scenarios in the Challenger mining environment in order to affect transfer. In this manner, participants would have been able to apply methods for resolution within FUMES that were consistent with emergency evacuation procedures used in the real world mine.

The second of these performance trends also indicates that participants used their real world

experience at Challenger to facilitate resolution of the problem-solving task. Participants demonstrated that they could identify the ideal refuge chamber during a simulated emergency evacuation scenario, which suggested an understanding of the environmental factors to consider during an evacuation. However this was far more prevalent in the first and third problem-solving instances, where only half of all participants who successfully evacuated to a refuge chamber in the second problem-solving instance selected the ideal refuge chamber. This could be attributed to the the complexity of the second problem-solving instance, where the user's starting location made the process of determining the ideal refuge chamber more arbitrary compared to problem-solving instance one and three (Tables 4.16 and 5.9). Taking this into consideration, the ability of participants to reliably select the ideal refuge chamber for evacuation suggests that existing knowledge of emergency evacuation procedure within the Challenger mining environment was being utilised effectively.

The performance data represented in Figures 6.1, 6.2, and 6.3 also demonstrates that participants experienced some problems in achieving positive outcomes throughout all three problem-solving instances:

- Participant performance tended to degrade with each subsequent problem-solving instance. This was particularly evident in the third problem-solving instance, where only slightly more than half of the participants were able to evacuate to a refuge chamber, and;
- Less than half of the participants who were able to evacuate to a refuge chamber in the first and second problem-solving instances utilised the ideal route to get there. Furthermore, of the participants who were able to evacuate to a refuge chamber during the third problem-solving instance, only one utilised the ideal route.

These trends suggest that participants were not consistently able to apply their existing real world knowledge within FUMES. However, these negative trends in participant performance can be ascribed to the design of the problem-solving task and the algorithm used by FUMES to evaluate whether the ideal route had been followed.

The problem was represented such that each problem-solving instance was more ill-structured, complex, and domain specific than the one that preceded it (Chapter 4.3.4). Each problem-solving instance supplied the user with less explicit information in turn (Table 5.8). Furthermore, the user also faced increased complexity and greater demands in their knowledge

of the problem domain in relation to their initial location, proximity to refuge chambers, and proximity to the vehicle fire and the severity and spread of the smoke emanating from it (Table 5.9). Given that structuredness, complexity, and domain specificity are factors which are known to affect problem-solving performance (Herron, 1990; Jonassen, 2000; Smith, 1988), it is reasonable to associate the decline in performance evident throughout Figures 6.1, 6.2, and 6.3 with the increasing difficulty of the problem-solving task.

The general inability of participants to use ideal routes to refuge chambers can be accounted for by the evaluation process utilised by FUMES to determine whether an ideal route had been followed. Due to time constraints during development, the technical implementation of this process was not very sophisticated and merely compared the user's route to a pre-determined ideal route according to which sections of the mine had been traversed (Table 5.14). While this did provide a basic means to determine whether the ideal route had been followed, it was infeasible in that it did not account for slight variations or deviations which might have otherwise suggested that the user had followed the ideal route to a refuge chamber. Thus, the data presented in Figure 6.2 only reflects participants whose route to a refuge chamber exactly matched the pre-determined ideal route, and does not account for the extent and significance to which deviations from this route may have occurred. Further insight into participants' route through the virtual mine was evident in the data collected via the input logs, which is documented in the following section.

Based on the structuredness, complexity, and domain specificity of the problem-solving task, and the way in which the ideal route was evaluated within FUMES, the negative trends observed in the participant performance data can be accounted for. This indicates that overall, participants were able to achieve positive outcomes related to successful evacuation to the ideal refuge chamber due to similarities between the problem-solving activity and emergency evacuations at Challenger. This infers both the application of existing real world knowledge pertaining to emergency evacuations within the Challenger mining environment, and the occurrence of learning transfer in accordance with the inverse transfer of training method for measuring learning transfer.

6.1.2 Input Logs

Keystroke and mouse interaction was recorded in a series of input logs for each participant by FUMES, allowing for a complete recording to be played back for observation in real time

(Chapter 3.3). As a result, participant performance could be re-produced for analysis of the actions they undertook within the virtual mining environment.

The input logs were examined for evidence of the positive outcomes that related to efficiency, self-rescuer usage, escape rise usage, and encounters with smoke and fire within FUMES (Table 6.1). The behavioural characteristics of participants that were utilised to determine the occurrence of these positive outcomes are listed in Table 6.2, as follows:

Table 6.2. Behavioural characteristics used to determine positive outcomes in FUMES

Positive outcome	Relevant behavioural characteristics as observed via input logs
Efficiency	· Speed at which participants moved through the mine · Extent to which participants used the ideal path to a refuge chamber · Tendency for participants to travel up or down the decline · Extent to which participants demonstrated awareness of where they were and where they were going within the virtual mine.
Self-rescuer usage	· Circumstances under which participants would activate their self-rescuers
Escape rise usage	· Circumstances under which participants would use escape rises within the virtual mine
Encounters with fire and smoke	· Participant responses to fire and smoke when encountered

Due to some technical issues with the input logging and playback process, only 25 input recordings were available for analysis, from which the following trends were observed:

Efficiency
· Participants tended to walk through the virtual mine, although they did run unnecessarily on some occasions;
· Participants tended to travel downwards through the mine during the first two problem-solving instances, and upwards through the mine during the third problem-solving instance. This is consistent with the locations of the ideal refuge chambers for each of these problem-solving instances;
· Participants who appeared disorientated tended to be more likely to deviate from the ideal route to a refuge chamber for a given problem-solving instance. Those participants who appeared to be disorientated tended to repeatedly look around the virtual mining environment in an effort to locate a visual cue that would give them an indication as to the their location, and;
· Participants appeared more likely to suffer from disorientation in the side-shafts,

rather than the main decline, where less visual cues were available for way-finding and navigation

Self-rescuer usage

- Participants tended to activate their self-rescuers when they encountered smoke and began coughing, although some activated their self-rescuers upon observing the vehicle fire during the second problem-solving instance, and;
- Participants tended to initially remain within the smoke, still coughing, while equipping their self-rescuers. Some participants did fail to move out of the smoke before overexposure occurred, but most moved out of the smoke after a few seconds to finish equipping their self-rescuers

Escape rise usage

- Participants tended to avoid using escape rises unnecessarily, although they were sometimes used when participants appeared disorientated, especially if this disorientation occurred in within a side-shaft, and;
- Participants made appropriate use of escape rises during the second problem-solving instance to circumvent the vehicle fire that was blocking access to the decline. Very few participants attempted to walk around the vehicle fire

Encounters with fire and smoke

- Participants tended to avoid fire and were generally quick to equip their self-rescuers when smoke was encountered;
- Participants tended to have no hesitation in moving through smoke affected areas once their self-rescuer had been activated, and;
- Smoke, particularly during the third problem-solving instance, appeared to be a leading cause of disorientation.

The trends in the input log data indicated that participants achieved positive outcomes relating to efficiency, self-rescuer usage, escape rise usage, and encounters with smoke and fire. Participants were observed to be generally efficient traversing the virtual mining environment, although disorientation was shown to affect their ability to use the ideal route to a refuge chamber, and more likely to occur in side-shafts rather than the main decline. Appropriate use was made of escape rises and self-rescuers, although some issues were identified regarding escape rise usage when disorientated, and self-rescuer application when exposed to smoke.

Participants tended to avoid contact with fire, but encounters with smoke were much more difficult to circumvent and disorientated participants, particularly during the third problem-solving instance.

The tendency of smoke to cause disorientation was also consistent with previous analysis which demonstrated that participant performance degraded in response to the severity of environmental conditions within the virtual mine (Chapter 6.1.1). The number of participants who successfully reached a refuge chamber and the number of participants who evacuated to a refuge chamber using the ideal route declined throughout the series of three problem-solving instances. This was consistent with the design of the problem representation, whereby the severity and spread of smoke in the virtual mine was increased with each successive problem-solving instance (Chapter 4.3.4).

Collectively, the trends in the input log data indicated that participants used knowledge of the real world Challenger mine during problem-solving activity in FUMES. Participants demonstrated behaviour that adhered to Challenger emergency evacuation protocol regarding efficient traversal of the mining environment, appropriate use of escape rises and their self-rescuer, and avoidance of smoke and fire where possible. This indicated the presence of learning transfer in accordance with the inverse transfer of training measure.

6.1.3 Observations Made by Training Staff

A Training Staff Member at the Challenger mine was used during the study to process participants through FUMES and assist Novice Participants if they became severely disorientated or lost within the virtual mining environment (Chapter 3.3). Therefore, the Training Staff Member was interviewed about his observations of participant behaviour, to provide an indication as to the presence of learning transfer.

Responses from the Training Staff Member indicated that participants were effectively able to use their existing knowledge of emergency evacuations at Challenger within FUMES. The Training Staff Member stated that participants responded to the auditory cues which were used to state the problem (Chapter 5.2.2.2) and the icon used to denote stench gas (Chapter 5.2.3.1) by immediately seeking refuge within the virtual mine. This suggested that participants were quickly able to recognise the context of the problem-solving task within FUMES based on their existing knowledge of the emergency broadcast and stench gas systems used to declare an

evacuation at Challenger.

However, further observations by the Training Staff Member suggested that Experienced Participants were able to apply existing knowledge more effectively within FUMES than Novice Participants. The Training Staff Member observed that Experienced Participants had a good understanding of their location as they moved through the virtual mine. In contrast, Novice Participants were observed to experience great difficulty in maintaining locational awareness and required assistance from the Training Staff Member to orientate themselves and locate a refuge chamber. This suggested that Experienced Participants had a better developed understanding of the layout and structure of the Challenger mining environment and were thus able to utilise this knowledge to navigate more effectively through the virtual mine than Novice Participants.

6.1.4 Summary for Inverse Transfer of Training

The inverse transfer of training method assumes the presence of learning transfer when users who are familiar with a real world task are able to achieve positive outcomes while performing the same task within a corresponding simulator. To this end, a collection of positive outcomes were identified based on the metrics used to evaluate how successfully personnel evacuated from the Challenger mine during a real world emergency. Data collected by FUMES in the form of performance measures and input logs were analysed in order to ascertain whether participants had achieved these positive outcomes with a view towards establishing the presence of learning transfer. This analysis was further supplemented by observations made by the Training Staff Member responsible for administering participants on site at Challenger during the study.

Analysis of the performance measures recorded by FUMES indicated that participants achieved the positive outcome of evacuation to a refuge chamber on the clear majority of occasions. Positive outcomes were also achieved during the first and third problem-solving instances involving location of the ideal refuge chamber. However, participants were less successful during the second problem-solving instance as their starting location made the process of determining the ideal refuge chamber more arbitrary. Performance measure analysis also suggested that participants experienced difficulty recognising the ideal route to refuge and that positive outcomes were achieved less frequently the further they progressed through the series of three problem-solving instances. This can be attributed to the overly simplistic evaluation of ideal routes by FUMES and the design of the problem-solving task, whereby each problem-

solving instance was more ill-structured, complex, and domain specific than the one that preceded it.

The input logs provided a means by which to analyse participant behaviour within FUMES for evidence of positive outcomes that related to efficiency, self-rescuer usage, escape rise usage, and encounters with fire and smoke. A number of trends were observed in these input logs which suggested that participants were behaving in accordance with emergency evacuation protocol at Challenger. Disorientation was found to affect the ability of participants to traverse the mining environment efficiently, with smoke being a contributing factor. These findings were consistent with those obtained via analysis of the performance measures, whereby the decline in participant performance throughout the series of three problem-solving instances corresponded with the severity of smoke within the virtual mine.

Observations made by the Training Staff Member indicated that the auditory cues used to state the problem and the icon used to denote stench gas resonated with participants such that they immediately recognised the need to seek refuge within the virtual mine. The Training Staff Member also acknowledged that Experienced Participants were better able to maintain locational awareness within the virtual mine compared to Novice Participants, who were observed to struggle in comparison.

Based on analysis of the performance measures, input logs, and Training Staff Member observations, it can be surmised that participants were able to achieve positive outcomes in FUMES via the application of existing knowledge pertaining to emergency evacuations in the Challenger mining environment. Participants were able to evacuate to refuge within the virtual mine and did so in a manner that was consistent with the established real world procedures used at Challenger. While participants were not able to achieve positive outcomes with the same degree of consistency throughout all three problem-solving instances, this decline in performance could be attributed to the design of the problem-solving task. Experienced Participants demonstrated a greater ability to maintain locational awareness than Novice Participants, who required assistance from the Training Staff Member to locate refuge chambers within the virtual mine. While this suggested that participants from both groups were benefiting from learning transfer within FUMES, it was clearly more pronounced for Experienced Participants as a result of their better developed understanding of the Challenger mining environment.

6.2 Assessment of Fidelity

The assessment of fidelity method for measuring learning transfer is used as a means of describing the physical similarity between the simulator and the real world environment being modelled, with the assumption being that higher fidelity will yield higher transfer (Lathan et al., 2002). Experienced Participants
and the Training Staff Member were selected to evaluate the fidelity of FUMES in this regard due to their familiarity with the Challenger mining environment and its emergency evacuation procedures.

Using a questionnaire, Experienced Participants were asked to what extent they felt the simulator represented the Challenger mine during an underground fire scenario. Their responses are summarised in Figures 6.4 and 6.5, as follows:

The simulation accurately represented the Challenger mining environment

number of participant responses (n) = 20
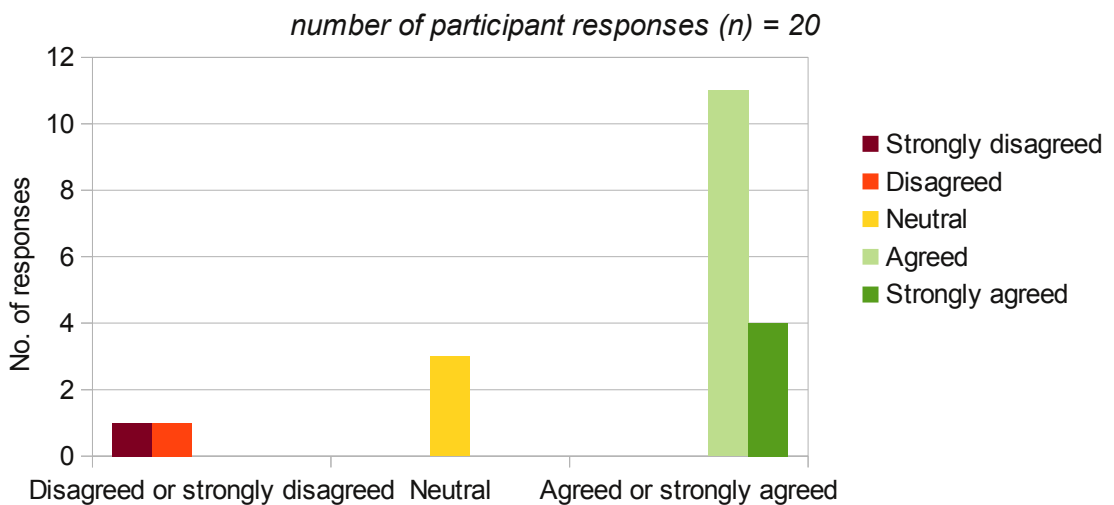
Figure 6.4. Accuracy with which FUMES represented the Challenger mining environment

**The simulation accurately represented the environmental conditions
at Challenger during a fire underground**
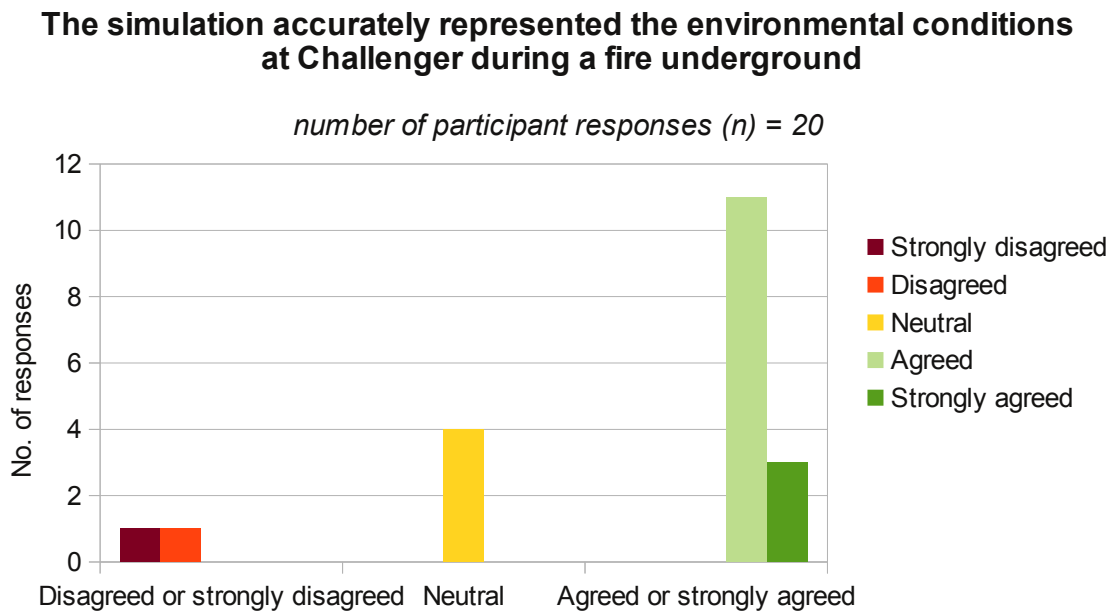
Figure 6.5. Accuracy with which FUMES represented the environmental conditions of an
underground fire scenario in the Challenger mine

Ignoring solitary outliers, the questionnaire responses presented in Figures 6.4 and 6.5
suggested that FUMES accurately represented the Challenger mine and the environmental
conditions during an underground fire. However, a number of comments provided by
Experienced Participants at the end of the questionnaire identified specific areas where the
accuracy of the representation was deficient.

The most common response from Experienced Participants in this regard pertained to a lack of
contextual detail in the virtual mining environment. Specifically, FUMES did not depict the
servicing infrastructure present within the real world mine with sufficient accuracy. Comments
indicated that such infrastructure could be used to aid way-finding and navigation within the
mine and that their absence made it more difficult to orient themselves and maintain awareness
of their location within the virtual mine. Figures 6.6 and 6.7 depict the servicing infrastructure
present within the Challenger mine, and that present within the virtual mine for the purpose of
comparison.

Figure 6.6. Servicing infrastructure running along the ceiling of a mine shaft in the Challenger mine

Figure 6.7. Servicing infrastructure running along the ceiling of a mine shaft in the virtual mine

In addition to the questionnaire responses, four Experienced Participants were also asked to assess the physical and functional similarity between FUMES and the real world mine at Challenger during interview. All four participants indicated that they were able to identify the virtual mining environment as a representation of the real world Challenger mine. Additional comments indicated that they could recognise areas in the virtual mine which were familiar to them, and that the locations of refuge chambers corresponded with those of the real world mine. Functionally, the interviewees indicated that movement through the virtual mine was consistent with the real world mine as far as the traversal of the decline, secondary shafts, and escape ways was concerned. However, two of the participants that were interviewed did indicate that they felt as though they were able to move more quickly through the virtual mine then they could through the real world counterpart. This perception could be attributed to the walking and running speeds for the user within the virtual mine, which were increased in order to reduce the amount of time users would spend travelling long expanses of the virtual mine (Chapter 5.2.1.8). Taking this into consideration, responses from the four Experienced Participants that were interviewed suggested that simulation environment was physically and functionally similar to the real world mine at Challenger.

However, as per the comments made at the end of the questionnaire, three out of the four

Experienced Participants interviewed also noted the inadequacy with which servicing infrastructure was represented within the virtual mine. One participant described the importance of servicing infrastructure in aiding orientation and navigation within an underground mine as follows:

> "A lot of underground mines have vent bags on the left and services on the right when you come out of drives and levels and onto the decline so in smoky conditions you always knew if you were going in the right direction. Like if you've got pipes and headers and that hanging down, if you were going along the right hand wall and feel them there, you knew you were going out of the level. But if you're going back in and feel them on the left, you know you're going the wrong way, in towards escape ways and stuff like that"

Echoing these sentiments, the Training Staff Member stated during interview that he noticed that some participants had problems orientating themselves due to the lack of servicing infrastructure in the virtual mine. The Training Staff Member identified the absence of vent bags, which are large yellow inflatable pipes which run along the ceiling in some sections of an underground mine (Figure 6.6), as being of particular relevance in this regard:

> "I think the biggest thing there was the vent bag. The vent bag is a good indicator of roughly where they are underground and what is looked for and where to go in the event of an emergency. So that was one of the bigger things that got their orientation a little bit lost."

Collectively, these responses confirmed the presence of some deficiencies in the representation of the Challenger mining environment. While responses did indicate that the fidelity of the virtual mining environment was sufficient overall, they also suggested that the absence of contextual details, specifically servicing infrastructure, affected the extent to which participants could utilise methods used for orientation and navigation in the real world mine.

This was consistent with observations made during analysis of the input logs (Chapter 6.1.2), whereby participants had a tendency to appear more disorientated in the side-shafts of the mine, rather than the main decline. While the main decline featured a number of additional navigational aids in the form of depth marking and escape rise signage, the side-shaft areas of the virtual mining environment contained only a basic representation of servicing infrastructure

to facilitate way-finding. This indicated that an absence of fidelity within the virtual mine regarding the representation of servicing infrastructure contributed to the disorientation of participants, which had a negative impact on problem-solving performance within FUMES.

6.2.1 Summary for Assessment of Fidelity

The assessment of fidelity method assumes the presence of learning transfer when a physical similarity exists between the simulator and the real world environment being modelled (Lathan et al., 2002). Given their experience in the Challenger mining environment, Experienced Participants and the Training Staff Member were consulted about the physical and functional similarity between FUMES and the real world Challenger mine during an emergency evacuation scenario.

Their responses suggested that FUMES was physically and functionally similar to the real world mining environment. Experienced Participants indicated that the virtual mine felt familiar to them based on their experiences at Challenger and that they were able to interact in a manner that approximated real world activity. However, a key distinction was evident regarding the representation of servicing infrastructure within the virtual mine. Subsequent feedback indicated that servicing infrastructure, such as the vent bag, were salient visual cues which aided orientation and navigation within the mining environment. This had a negative impact on participant performance, and had servicing infrastructure been represented with greater fidelity, participants could have been expected to be able to orientate themselves and navigate more effectively.

Overall, this demonstrated that FUMES provided sufficient fidelity for participants to recognise and be familiar with the virtual mining environment, but not enough for them to employ the full range of problem-solving strategies which would be used in the real world mine. Had vent bags and servicing infrastructure been represented with greater fidelity, participants would have been able to use their knowledge of real world navigation strategies within the virtual mine. This is consistent with the means by which the assessment of fidelity method measures transfer, whereby a higher level of fidelity implies greater learning transfer.

6.3 Operator Opinion

The operator opinion method evaluates the features, probable training impact on real world performance, and perceived training value of the simulator as a means of measuring learning transfer (Lathan et al., 2002). To this end, Experienced Participants and Novice Participants were presented with questionnaire prompts which were designed to elicit such opinions regarding their experience with FUMES. Their responses are presented in Figures 6.8 through 6.11, with Figure 6.12 providing an overall summary.

**The simulation would be a valuable training tool
for emergency evacuation procedures at Challenger**

number of participant responses (n) = 40

■ Experienced Participants (20 responses)
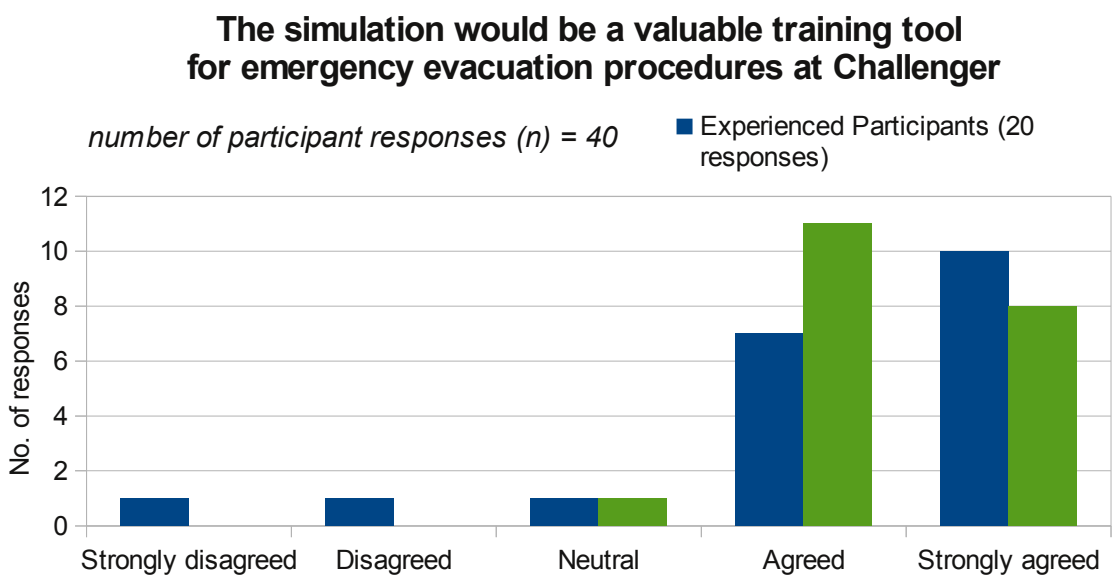
Figure 6.8. Value of FUMES as a platform for emergency evacuation training

The simulation accurately represented the emergency evacuation procedure at Challenger during a fire underground

number of participant responses (n) = 40

■ Experienced Participants (20 responses)
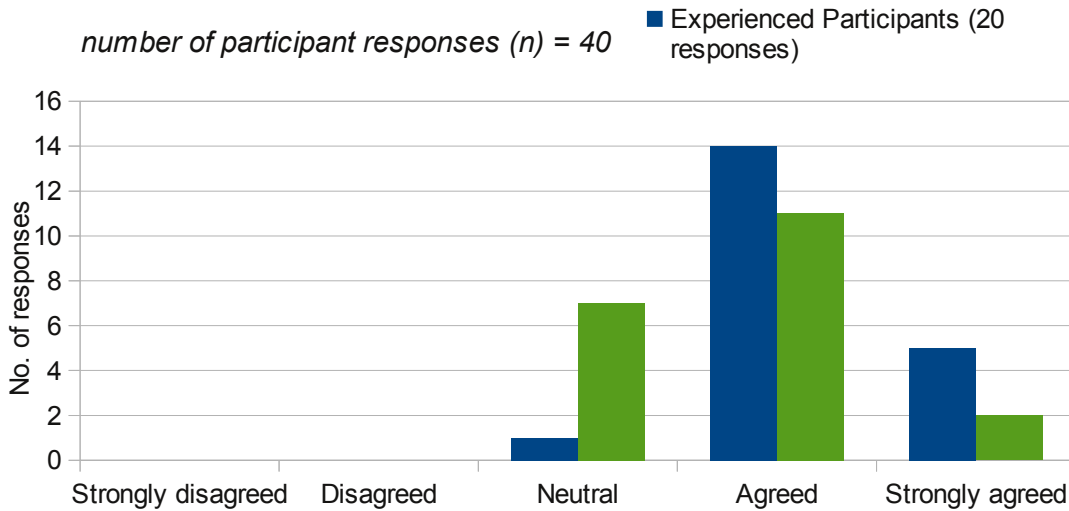
Figure 6.9. Accuracy with which FUMES represented the emergency evacuation procedure

The simulation had the necessary features for emergency evacuation training at Challenger

number of participant responses (n) = 40

■ Experienced Participants (20 responses)
■ Novice Participants (20 responses)
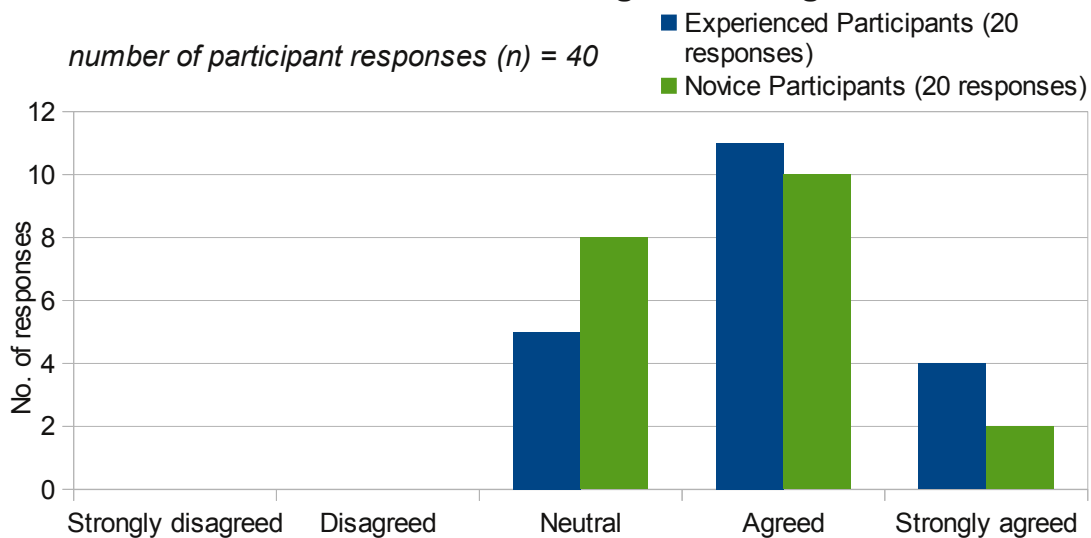
Figure 6.10. Extent to which FUMES possessed the necessary features for emergency evacuation training

Using the simulation could improve the performance of mining personnel during an emergency evacuation at Challenger

number of participant responses (n) = 36   ■ Experienced Participants (20 responses)
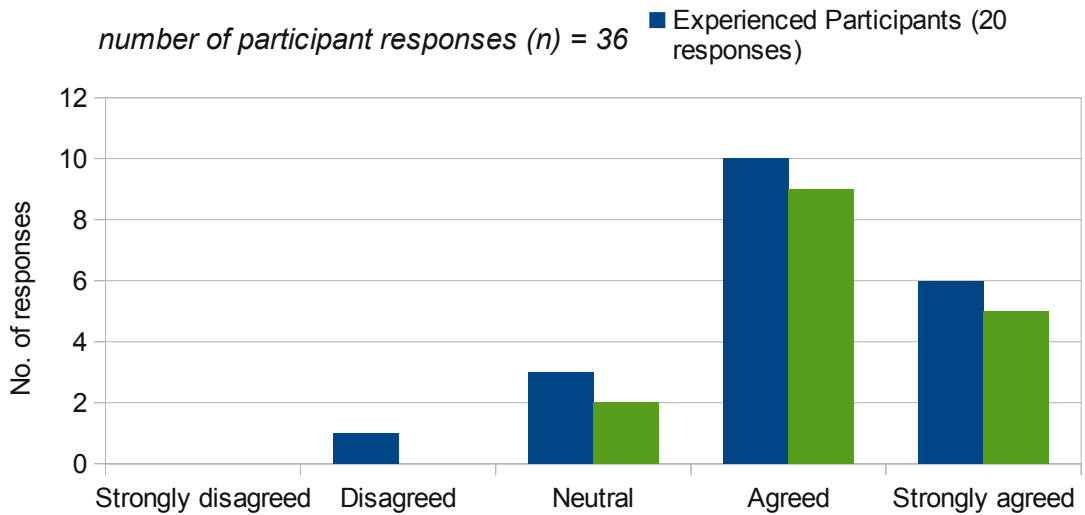
Figure 6.11. Potential impact of FUMES on the performance of mining personnel during a real world evacuation

Summarised operator opinion of FUMES

number of participant responses (n) = 156   ■ Experienced Participants (80 responses)
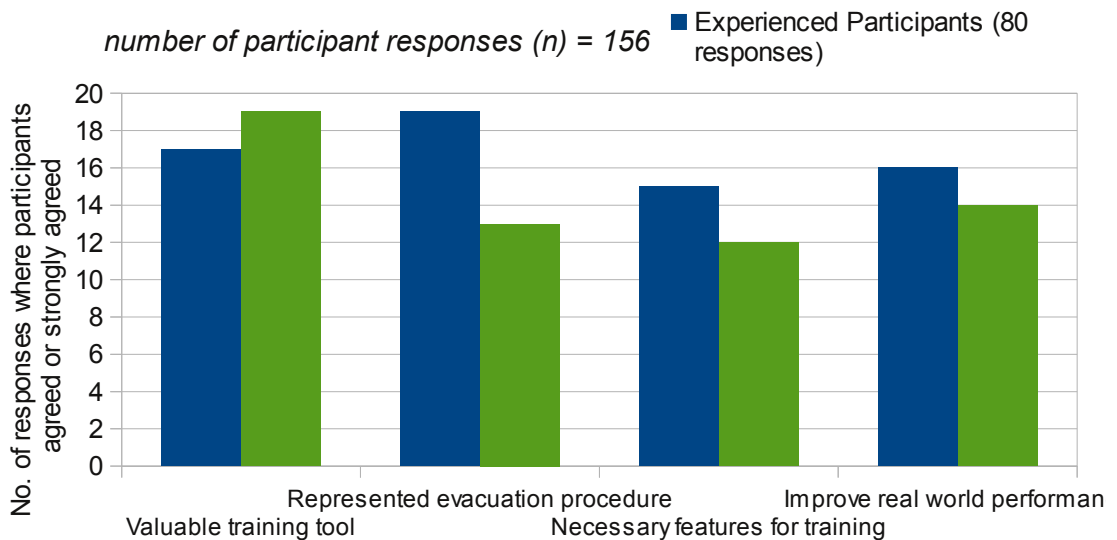
Figure 6.12. Summarised response of participant opinion of FUMES

The questionnaire responses demonstrated that participants recognised FUMES as a viable emergency evacuation training platform for personnel at the Challenger mine (Figures 6.8

through 6.11). This was evident for both Experienced Participants and Novice Participants, which suggests that FUMES would be suitable for training mining personnel with varying levels of existing experience at Challenger. The general trend in responses indicated that Experienced Participants tended to have an overall higher opinion of FUMES than Novice Participants, but that Novice Participants responded slightly more positively in relation to the value of FUMES as a training tool (Figure 6.12).

These questionnaire responses were consistent with remarks provided by interviewed participants regarding the value that FUMES would have in training Challenger mining personnel to deal with real world emergency evacuations. Responses from the three Novice Participants who were interviewed indicated that personnel with little experience at Challenger could utilise FUMES to familiarise themselves with emergency evacuation procedures within this environment. Comments from these interviewees emphasised the ability of the simulator to provide users with an encounter that could be related to in absence of real world experience, allowing them to develop an awareness as to what to expect during an emergency evacuation before commencing occupational duties within the Challenger mine.

Responses from the four Experienced Participants who were interviewed accentuated the experiential nature of FUMES in the development and maintenance of knowledge for emergency evacuation procedures in the Challenger mining environment. Feedback from these interviewees indicated that experienced personnel at the mine could utilise FUMES to sustain their existing knowledge within a context of practice that was feasible and accessible beyond the confines and restrictions imposed by operations in the real world mining environment.

The Training Staff Member was also queried about the training value of FUMES given his background in processing personnel through the existing induction training program at the mine. His comments reflected the questionnaire and interview responses provided by Experienced Participants, in that he too saw value in FUMES as an experiential training platform with the ability to refresh and reinforce existing knowledge. The Training Staff Member praised FUMES for its ability to maintain awareness and further understanding of key equipment such as the self-rescuer, especially for personnel who had long since undertaken induction training and not had further training since. Furthermore, the Training Staff Member also emphasised the ability of FUMES to develop critical thinking and decision making skills during the emergency evacuation process, with the added benefit of being able to experience and learn from the outcomes of said decisions within the training environment.

6.3.1 Summary for Operator Opinion

While the responses provided by both groups of participants and the Training Staff Member indicated a positive regard for FUMES as a platform for Challenger emergency evacuation training, it is worth noting that these opinions are subjective and do not necessarily imply the presence of learning transfer. The operator opinion method for measuring learning transfer is useful when performance testing is not feasible, but may fail to recognise whether improvements in user performance are the result of previous knowledge and experience and not the simulator (Lathan et al., 2002). However, two different groups of participants with different degrees of experience at Challenger recognised the value of FUMES as a training platform for developing knowledge for use during real world emergency evacuations. This was further substantiated via comments made by the Training Staff Member, who suggested that the experiential nature of the FUMES training platform could be used to expose trainees to scenarios to that they were not familiar with. While the operator opinion method does have it's limitations, it is still of value via triangulation with the inverse transfer of training and assessment of fidelity methods for determining the presence of learning transfer.

6.4 Summary of Findings for Learning Transfer

Addressing the first research question required the data collected during the FUMES implementation to be examined for evidence of learning transfer with a view towards determining how problem-solving knowledge and skills could be transferred between a virtual and corresponding real world environment. To this end, three different measures for learning transfer were utilised, consisting of the inverse transfer of training method, assessment of fidelity method, and operator opinion method (Lathan et al., 2002).

Analysis of the data collected for the inverse transfer of training method indicated that participants were able to utilise existing knowledge of emergency evacuation scenarios at Challenger during problem-solving activity within FUMES. Participants demonstrated the ability to achieve outcomes within the simulator which were consistent with successful real world emergency evacuations of the Challenger mine. While the achievement of positive outcomes declined with each successive problem-solving instance, this was accounted for by the design of the problem-solving task, which placed increasing demands on participants in the form of greater ill-structuredness, complexity, and domain specificity.

Chapter 6   Research Question 1 – Transfer of Learning

Evaluation of the data utilised for the assessment of fidelity method suggested that FUMES adequately represented the Challenger mining environment during an underground fire emergency evacuation scenario. However, participant responses demonstrated that a lack of fidelity of the representation of mining infrastructure had a negative impact on their performance in terms of orientation and navigation. The lack of fidelity in this area was found to be consistent with earlier observations of participant performance, which found that participants were more likely to become disorientated in areas of the virtual mining environment with the least amount of contextual detail.

Data analysed for the operator opinion method revealed that participants recognised FUMES as a suitable platform for Challenger mining personnel to undertake emergency evacuation training. Participants with less experience at the mine emphasised the value of FUMES as a familiarisation tool, while those participants with more experience saw value in FUMES as a training environment in which existing knowledge could be applied experientially in addition to a means by which to refresh existing knowledge. The Training Staff Member at Challenger also emphasised the value of FUMES as a training platform in which the decision making process during an emergency evacuation scenario could be acted out and learned from. Collectively, the analysis undertaken using the inverse transfer of training, assessment of fidelity, and operator opinion methods demonstrated the presence of learning transfer. Participants were able to utilise their knowledge of the Challenger mining environment and it's emergency evacuation protocols to successfully undertake problem-solving tasks within FUMES that were situated in a similar context. This was more evident for Experienced Participants who had a greater wealth of knowledge to draw upon based upon their occupational experience at the Challenger mining facility.

These findings demonstrated that problem-based learning environments implemented using 3D gaming technologies could be used to promote learning transfer for real world contexts. In order for this to occur, the problem-based learning environment needs to elicit users' existing knowledge of the problem domain to provide them with the means to resolve the problem-solving task and develop their understanding. Problem-solving activity must be experientially focussed and reflect the nature and characteristics of the real world problem such that users can learn how to resolve the real world problem via the application of knowledge in practice. Furthermore, the 3D simulation environment is required to replicate the physical and functional characteristics of the real world environment with sufficient fidelity so as to provide the user with a familiar context in which the methods used to resolve the real world problem can be

utilised consistently.

In this instance, learning transfer was evident in the three indirect methods used. This demonstrates that FUMES was effective in developing knowledge for use during real world emergency evacuations at Challenger, but it does not show how the SUPL Design Framework contributed to this effectiveness. This will be explored in the next chapter with a view towards validating the SUPL Design Framework as an approach for designing problem-based learning environments.

7 Research Question 2 – The SUPL Design Framework

In answering the first research question, the previous chapter evaluated the effectiveness of FUMES in terms of its ability to develop knowledge for use during real world emergency evacuations at Challenger. Three different measures of learning transfer were used to analyse the data collected during the study, with findings indicating that participants used their existing knowledge of emergency evacuations at Challenger to engage with the problem-solving task in FUMES. This chapter explores the effectiveness of the SUPL Design Framework in fostering this learning transfer in order to address the second research question:

Question 2. What design considerations are needed to support knowledge construction and transfer in a 3D, problem-based learning environment? Specifically, what design considerations are relevant to the user, the problem-solving task, and the 3D simulation environment?

Answering the second research question entailed validating the design considerations identified in the SUPL Design Framework (Figure 7.1). These design considerations were identified from a review of the literature and synthesised into a design framework for supporting knowledge construction and transfer in 3D problem-based learning environments (Chapter 2.5). FUMES was implemented using the SUPL Design Framework in order to address real world emergency evacuation training requirements at the Challenger mine (Chapter 4).

Chapter 7   Research Question 2 – The SUPL Design Framework
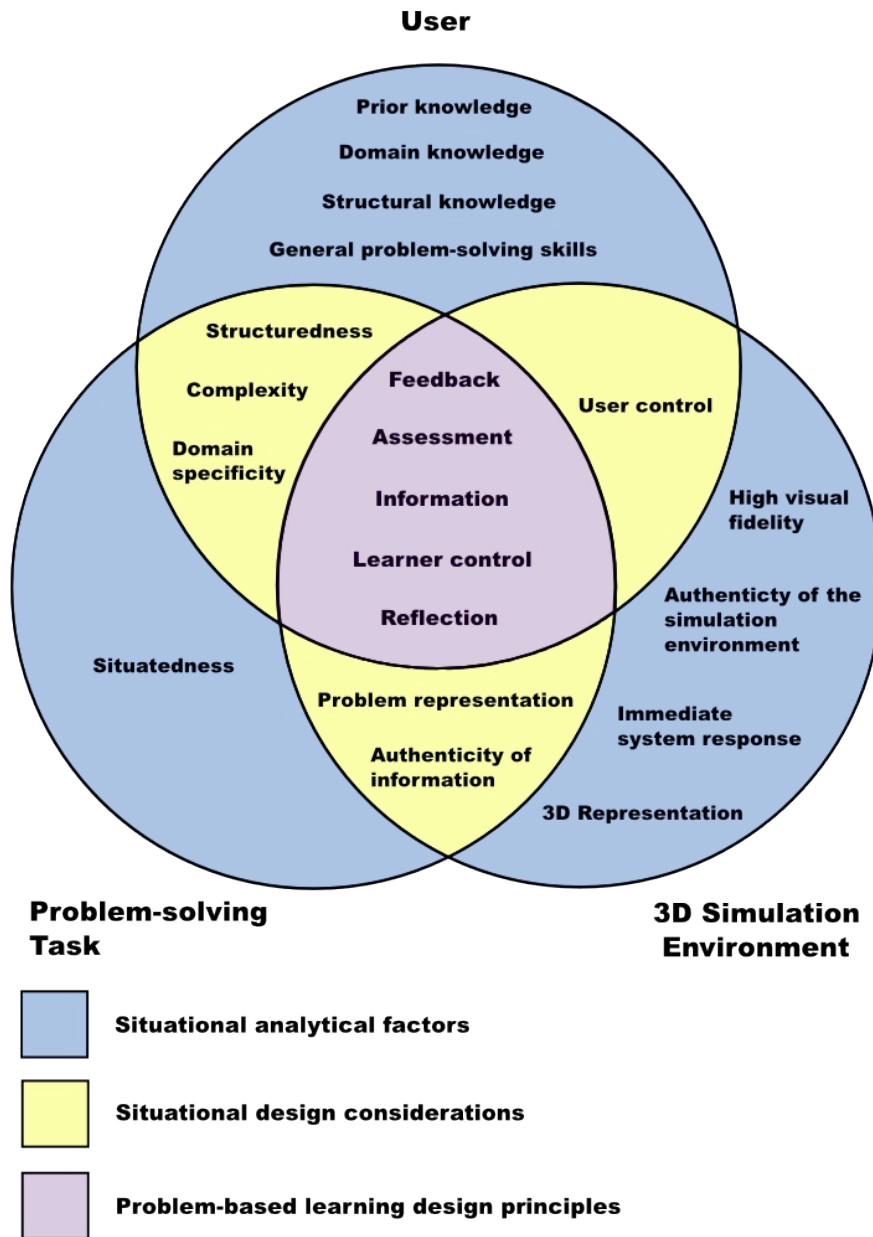
Figure 7.1. The SUPL Design Framework established to address the second research question

The data collected during the study was analysed to establish the veracity of each design consideration detailed in the SUPL Design Framework and identify findings which could be used to guide their implementation. Questionnaire, interview, and performance data recorded by FUMES was analysed for 21 Experienced Participants, who had at least six months full time experience at the Challenger mine, and 20 Novice Participants, who were new employees at the mine. A constant comparative approach to analysis was employed for each design consideration identified in the SUPL approach as follows:

Chapter 7   Research Question 2 – The SUPL Design Framework

- Chapter 7.1 evaluates the extent to which Situational Analytical Factors were accommodated during the FUMES implementation;
- Chapter 7.2 examines the efficacy of Situational Design Considerations during the FUMES implementation (Chapter 7.2), and;
- Chapter 7.3 investigates the impact of Problem-Based Learning Design Principles on the learning process during the FUMES implementation.

7.1 Situational Analytical Factors

Situational Analytical Factors are design considerations that exist outside the control of the designer which need to be identified and subsequently accommodated in order to support knowledge construction and transfer within a 3D, problem-based learning environment (Chapter 2.5). The role of Situational Analytical Factors during the FUMES implementation and their validity as design considerations is to be explored in the following sections:

- Chapters 7.1.1 through 7.1.4 examines prior knowledge, domain knowledge, structural knowledge and general problem-solving skills;
- Chapter 7.1.5 scrutinises the situatedness of the problem-solving task, and;
- Chapters 7.1.6 through 7.1.9 appraise 3D representation, immediate system response, high visual fidelity, and authenticity within the 3D simulation environment.

7.1.1 Prior knowledge

Prior knowledge consists of the knowledge acquired during previous problem-solving experience that is called upon when presented with a problem which is in some way similar. Situation analysis established that existing induction training provided participants with problem-solving experience in determining the appropriate course of action to take to reach refuge in response to an underground fire emergency at Challenger (Chapter 4.2.1). Participants were required to traverse levels of the mine using both the main decline and escape rises to reach a refuge chamber in order to demonstrate what may be required in the event of an emergency.

The following sections detail the data analysis for prior knowledge as a means of determining the extent to which this Situational Analytical Factor was accommodated within FUMES. This

Chapter 7   Research Question 2 – The SUPL Design Framework

was undertaken according to evaluation criteria established from the literature (Table 2.14) pertaining to previous experience with contextually similar problems, identification of unknown entities in the problem, and evidence of learning transfer.

Previous Experience with Contextually Similar Problems

Questionnaire prompts were used to identify participants' previous experience with problems which were contextually similar to those presented in FUMES. Experienced Participants and Novice Participants were queried as to their previous experience with emergency evacuations at Challenger, and previous experience with emergency evacuations at other underground mines (Figures 7.2 and 7.3):

I have previous experience with emergency evacuations of the Challenger mine

total number of participant responses (n) = 41

■ Experienced (21 responses)
■ Novice (20 responses)
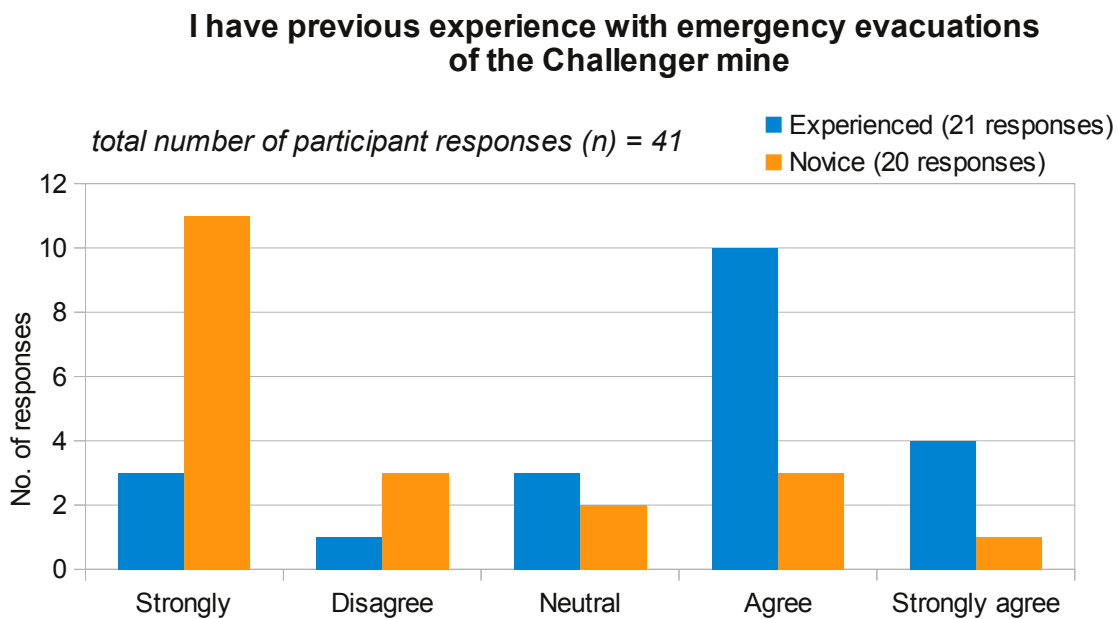
Figure 7.2. Previous experience with emergency evacuations at Challenger

Chapter 7   Research Question 2 – The SUPL Design Framework

I have previous experience with emergency evacuations of other underground mines
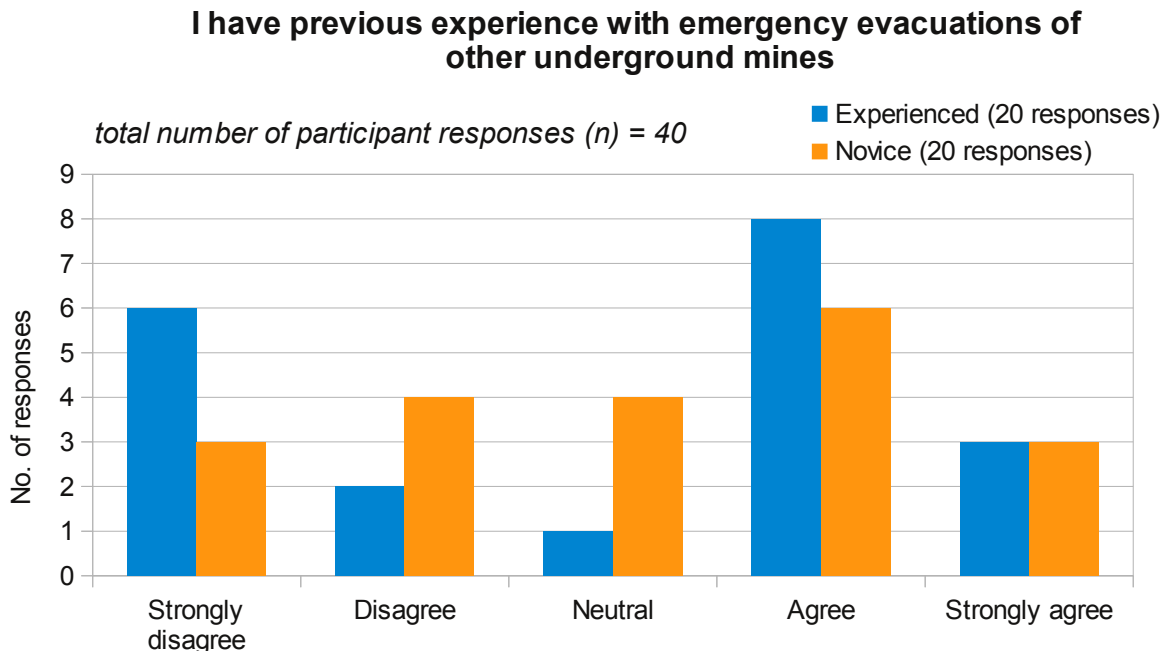
Figure 7.3. Previous experience with emergency evacuations at underground mines other than Challenger

Experienced Participants, who had at least six months full time experience as employees at Challenger, were understandably more familiar with emergency evacuations at Challenger than Novice Participants (Figure 7.2). However, previous experience with emergency evacuations in other underground mines appeared to be reasonably equitable between Experienced and Novice Participants (Figure 7.3).

This was reflected in interview responses relating to the existing experience that participants drew upon to assist them during problem-solving activity in FUMES. All four of the Experienced Participants who were interviewed indicated that they made use of existing spatial knowledge of the Challenger mine in terms of its layout, spatial cues, and locations of escape ladders and refuge chambers. In contrast, interview responses from the three Novice Participants suggested that little of their previous experience was of assistance to them.

Collectively, the questionnaire and interview responses indicated that Experienced Participants had more extensive experience with contextually similar problem-solving activity than Novice Participants. Experienced Participants were more familiar with emergency evacuations of the Challenger mine and were able to utilise spatial knowledge that had been acquired within this

environment to navigate within the virtual counterpart, which suggested that the two environments were similar. In contrast, the Novice Participants demonstrated that they were relatively unfamiliar with emergency evacuations at Challenger and limited in their ability to utilise contextually relevant prior knowledge within FUMES.

Identification of Unknown Entities in the Problem

Interview prompts were used to identify which aspects of problem-solving activity within FUMES were unknown or unfamiliar to participants. Interview responses from the four Experienced Participants indicated there was little that was unknown or unfamiliar, with one of these participants stating that nothing seemed unfamiliar to them at all.

In contrast, interview responses from two of the three Novice Participants emphasised uncertainty in relation to navigation and way-finding within the virtual mining environment. They described their experience using terms such as "lost", "didn't know where to go", and "like a maze", despite the fact that participants in this group were provided with a Mine Layout Diagram whilst using FUMES (Appendix 4). This suggested that the Mine Layout Diagram, which depicted a two-dimensional cross section of the mine, detailing the depth of each level as well as the locations of refuge chambers and escape rises, was an inadequate means by which to address Novice Participants' deficiency of prior knowledge in relation to navigation within the mining environment.

These interview responses were consistent with training staff observations. Experienced Participants demonstrated they were aware of their location and appeared to be familiar with the virtual mining environment. In contrast, Novice Participants had difficulty orientating and navigating within the virtual mine despite the provision of the Mine Layout Diagram. As such, the Training Staff Member indicated that he was required to assist nearly all Novice Participants to re-orientate themselves when they became lost within the virtual mine as they would have been unable to reach a refuge chamber otherwise. However, the Training Staff Member did indicate that both groups of participants were familiar with the objective of the problem-solving task , stating that "as they heard the emergency declaration within the simulator, they knew they had to get to refuge."

As a whole, the interview responses indicated that, while both groups of participants knew that

they had to evacuate to a refuge chamber when an emergency had been declared, Novice Participants were less certain of how to get there than Experienced Participants. This suggests that the goal of the problem-solving task appeared well-structured to both Novice and Experienced Participants, but that the solution method appeared more ill-structured to Novice Participants than Experienced Participants.

Evidence of learning transfer (real world to FUMES)

In the previous chapter (Chapter 6.1), learning transfer was identified by virtue of participants' ability to achieve positive problem-solving outcomes in FUMES. Participants demonstrated the application of existing knowledge which was contextually relevant to the problem-solving task to effect resolution in accordance with emergency evacuation procedures used at Challenger. However, Experienced Participants were more effective than Novice Participants as they demonstrated better locational awareness within the virtual mine, and unlike Novice Participants, were able to successfully resolve the problem-solving task without assistance from the Training Staff Member.

Experienced Participants also indicated that FUMES accurately represented the Challenger mining environment during an emergency evacuation scenario, despite the presence of some visual deficiencies. As a result, Experienced Participants were able to recognise the context in which problem-solving activity was situated by virtue of the physical and functional similarity between FUMES and the real world Challenger mine (Chapter 6.2).

Summary for Prior Knowledge

Prior knowledge needs to be accommodated within problem-based learning environments so that learners can utilise existing problem-solving experience to identify unknown entities and resolve the problem-solving task. Situation analysis indicated that participants had prior knowledge of emergency evacuations at Challenger as a result of familiarising themselves with the required course of action during induction training (Chapter 4.1). In order to accommodate this prior knowledge, problem-solving activity within FUMES was established within the context of emergency evacuations at Challenger, whereby participants were required to determine the appropriate course of action to reach refuge in response to an underground fire emergency within a 3D representation of the Challenger mining environment.

Chapter 7   Research Question 2 – The SUPL Design Framework

Findings elicited from the FUMES implementation regarding participants' previous experience with contextually similar problems, their identification of unknown entities in the problem, and evidence of learning transfer indicated that Experienced Participants possessed a greater extent of contextually relevant prior knowledge than Novice Participants. This provided Experienced Participants with the knowledge needed to orientate and navigate effectively within the virtual mine, and as such, the problem-solving task appeared more familiar to them than their novice counterparts. Experienced Participants demonstrated that they could recognise the context of the problem-solving task as a result of the physical and functional similarity between FUMES and the Challenger mine during an emergency evacuation. In contrast, Novice Participants were less certain of how to navigate within the virtual mine, and despite having access to a Mine Layout Diagram, required assistance from the Training Staff Member in order to reach a refuge chamber. This suggested that existing induction training did not instil participants with the ability to effectively navigate within the Challenger mine. However, both groups of participants demonstrated that they were clearly aware of the objective of the problem-solving task.

This suggested that FUMES effectively accommodated the real world prior knowledge of participants, although this was more evident for Experienced Participants as a result of greater familiarity with the real world problem. This further demonstrated that the problem-solving task within FUMES was situated within a context that was similar to that of emergency evacuations within the Challenger mine. While such findings may appear somewhat self evident, they reinforce the importance of eliciting prior knowledge towards the resolution of the problem, as shown in the SUPL Design Framework.

This indicates the need to identify and accommodate the prior knowledge of users in order to support the construction and transfer of knowledge in 3D, problem-based learning environments. Analysis of the data collected during the FUMES implementation indicates the following findings in relation to the prior knowledge situational factor:

- The problem-solving task must be situated with respect to the problem-solving experience that prior knowledge is to be elicited from. In practice, this means that one should employ cues which establish the physical and functional similarity between the context of the problem-solving task and that of the real world problem in order to encourage the transfer of knowledge.

Chapter 7   Research Question 2 – The SUPL Design Framework

7.1.2 Domain knowledge

Domain knowledge concerns the specific knowledge of the user required to perform tasks relevant to the learning context. Induction training provided participants with domain knowledge pertaining to the characteristics of the Challenger mine, the function of the cap-lamp and self-rescuer, and the sequence of actions required as part of the emergency evacuation procedure (Chapter 4.2.2). Through this training, participants were deemed to have an understanding of the manner in which an emergency evacuation was initiated, the role of escape rises and refuge chambers, spatial cues within the mine, and the environmental conditions likely to be present during an underground fire.

The following sections detail the data analysis for domain knowledge as a means of determining the extent to which this Situational Analytical Factor was accommodated within FUMES. This was undertaken according to evaluation criteria established from the literature (Table 2.14) pertaining to the identification of objects, events, and ideas relevant to the problem and identification of information necessary for resolving the problem.

Identification of Objects, Events, and Ideas Relevant to the Problem

Four Experienced Participants and three Novice Participants were interviewed to identify the objects, events, and ideas that they considered relevant to problem-solving activity. Experienced Participants indicated they considered their proximity to the obstruction or emergency, the location of the nearest refuge chamber, and the ideal route to take through the virtual mine as being important:

- "... the big thing is your proximity to whatever the emergency was and then where you needed to get to.";
- "... trying to think about where the fire is and whether it is best to go up or down, and where the best refuge chamber is."
- "... consider the nearest refuge chamber, needed to consider where there was an obstruction and whether it was a good way to go up or down depending on where the obstruction was.", and;
- "...So I considered where the chamber was, where the obstructions or the incident might have been in relation to where I was, and then how much energy I was going to expend

getting there."

These responses suggest the application of procedural domain knowledge, which details knowledge of different strategies, heuristics, and algorithms which are relevant to the problem at hand, as well as the constraints under which each can be applied (Smith, 1988).

In contrast, Novice Participants identified the layout and structure of the virtual mine, including salient spatial cues, as relevant considerations during problem-solving activity in FUMES:

- "...where the fire was, if it was going to effect me if I went up or down, or walk out on to the decline ";
- "...which way was up";
- "...direction, what to look for like signage and stuff, depth, what levels you're looking for", and;
- "...what levels you're looking for."

Interview responses suggest that Experienced Participants had better developed domain knowledge than Novice Participants which they were able to utilise to greater effect within FUMES. Experienced Participants considered their proximity to hazards and the ideal route to take through the virtual mine to reach the nearest refuge chamber, while Novice Participants were more concerned with simply maintaining an awareness of their location. This suggested a deficiency in domain knowledge relating to spatial awareness which limited Novice Participants' ability to consider more significant issues during problem-solving activity in FUMES.

Identification of Information Necessary for Resolving the Problem

Four Experienced Participants and three Novice Participants were interviewed to identify information they needed to resolve the problem-solving task in FUMES. The Experienced Participants indicated they required knowledge of their initial location, proximity to the nearest refuge chamber, and proximity to hazards or obstructions to resolve the problem. This information was provided by the simulation to establish the initial state of the problem (Chapter 4.2.1), and was sufficiently adequate for Experienced Participants to achieve resolution:

- "I completed them all successfully based on what you gave me. I probably didn't do

them as fast as what was required, but I didn't die. So the information was probably satisfactory", and;

· "All the information that they gave us was pretty well what you needed."

These responses suggested that Experienced Participants used their existing domain knowledge in conjunction with the information provided at the onset of the problem to achieve resolution. This further demonstrated that Experienced Participants recognised the information needed for problem-solving activity within the statement of the problem.

In contrast, responses from novice interviewees emphasised the need for knowledge relating to navigation and the use of spatial cues within the mining environment:

· "The information I needed to know was where they (refuge chambers) were, which I had the layout of where they were on a piece of paper", and;

· "Knowledge of the Challenger mine would help a lot."

These comments suggested that Novice Participants had insufficient knowledge of the layout and spatial characteristics of the Challenger mining environment, and further demonstrated that information explaining how to navigate within the virtual mining environment was not expressed in the problem.

The interview responses thus indicated that both groups of participants were able to identify information that was necessary for undertaking problem-solving activity in FUMES. Experienced Participants acknowledged the information which established the initial state of the problem detailing their initial location and proximities to nearby refuge chambers and environmental hazards. Novice Participants recognised the need for knowledge of the layout and spatial characteristics of the mining environment, but their comments suggested a deficiency in this regard and were consistent with previous analysis which suggested that existing induction training did not instil participants with the ability to effectively navigate within the Challenger mine (Chapter 7.1).

Summary for Domain Knowledge

Learners rely on their knowledge of the problem domain to identify key objects, events, and ideas and determine the information needed to resolve the problem within problem-based

learning environments. Situation analysis indicated that participants possessed knowledge of the problem domain in relation to the spatial characteristics, visual cues, and conditions of the Challenger mine, in addition to the the role of escape rises, refuge chambers, cap-lamps, and self-rescuers during emergency evacuation procedures (Chapter 4.2.2). In order to accommodate this domain knowledge, the problem-solving task within FUMES was situated within a scale, 3D representation of the Challenger mining environment in which participants responded to an underground fire emergency in a manner consistent with real world protocol.

Findings elicited from the FUMES implementation demonstrated that both groups of participants recognised objects, events, and ideas that were relevant to the problem and could identify the information that they required to affect resolution. Experienced Participants recognised their proximity to hazards, the location of the nearest refuge chamber, and the ideal route to refuge as knowledge that was relevant to the resolution of the problem. Experienced Participants also acknowledged the information provided during the statement of the problem in this regard, which detailed their initial location, proximity to the nearest refuge chamber, and proximity to hazards or obstructions. In contrast, Novice Participants emphasised the relevance of knowledge pertaining to the layout, structure and spatial cues of the virtual mine during problem resolution. Novice Participants recognised that knowledge of the spatial characteristics of the Challenger mine was necessary for problem resolution, but acknowledged that their existing knowledge was deficient in this regard. This limited their ability to consider the more significant aspects of the problem-solving task and suggested that they lacked the procedural domain knowledge required to utilise spatial information to navigate effectively within the mining environment.

This suggested that FUMES effectively accommodated the real world domain knowledge of participants, although this was more evident for Experienced Participants than Novice Participants. Responses provided by Novice Participants suggested that existing induction training did not instil sufficient declarative domain knowledge relating to the layout and spatial characteristics of the Challenger mine. Such knowledge was required for effective navigation within FUMES, and as such, Novice Participants struggled to orientate themselves and navigate within the virtual mine (Chapter 7.1). The more extensive domain knowledge of Experienced Participants afforded them greater familiarity with the problem domain and also allowed them to effectively identify the gaps between their existing knowledge, and the knowledge that was required to affect resolution. This demonstrated the need for greater scaffolding for Novice Participants within FUMES in order to address the deficiencies in their domain knowledge.

This indicates the need to identify and accommodate the domain knowledge of users in order to support the construction and transfer of knowledge in 3D, problem-based learning environments. Analysis of the data collected during the FUMES implementation indicates the following findings in relation to the domain knowledge situational factor:

- Entities within the simulation environment that accommodate domain knowledge need to be presented clearly so that users can recognise the problem domain, and in turn, determine the information needed to achieve problem resolution. This entails identifying familiar cues for representing domain knowledge during situation analysis and providing scaffolding for users in the event that their domain knowledge is determined to be inadequate.

7.1.3 Structural knowledge

Structural knowledge describes the organisation and interrelationships between concepts within the problem domain. Situation analysis established that existing induction training provided participants with structural knowledge detailing the relationships between movement speed, terrain inclination, physical exertion and self-rescuer oxygen consumption (Chapter 4.2.3). Participants understood that higher movement speed and greater terrain inclination had a more adverse effect on physical exertion, and in turn, self-rescuer oxygen consumption than slower movement speeds and less terrain inclination.

The following sections detail the data analysis for structural knowledge as a means of determining the extent to which this Situational Analytical Factor was accommodated within FUMES. This was undertaken according to evaluation criterion established from the literature (Table 2.14) pertaining to the identification of relationships in the problem domain.

Identification of Relationships in the Problem Domain

Four Experienced Participants and three Novice Participants were interviewed in relation to their perception of relationships amongst objects, actions, and events during problem-solving activity in FUMES. Responses from the Experienced Participants identified connections between the proximity of smoke and coughing, physical exertion and oxygen consumption, and

the characteristics of the cap lamp light on reflective surfaces. One Experienced Participant also indicated that the spread of smoke within the virtual mine was affected by ventilation and air flow.

In contrast, interview responses from the three Novice Participants indicated that they were unable to identify affiliations within the problem domain to the same extent as Experienced Participants. Two of these Novice Participants indicated that they were not aware of any related entities within the problem domain. However, the third Novice Participant did identify a relationship between the spread of smoke and the flow of air within the virtual mine. This same Novice Participant also alluded to a connection between physical exertion and oxygen consumption during responses to other interview questions.

Additional interview questions asked participants to describe the nature of the relationships between physical effort and movement, physical effort and breathing, and physical effort and oxygen consumption within FUMES. Responses provided by both Experienced Participants and Novice Participants identified the nature of these relationships as follows:

- Physical effort increased as the user moved faster;
- Physical effort increased the further the user moved through the mine;
- Physical effort increased if the user was moving up a decline or climbing an escape rise
- Breathing became more rapid as physical effort increased, and;
- Oxygen was consumed more quickly from the self-rescuer as the rate of breathing increased.

The consistency of interview responses suggested that FUMES represented these relationships with sufficient fidelity such that they could be readily recognised by both Experienced Participants and Novice Participants, although Experienced Participants provided greater detail in their descriptions.

Thus, the interview responses collectively demonstrated that Experienced Participants and Novice Participants were able to identify and describe relationships between objects, actions, and events within the problem domain. However, Experienced Participants exhibited a greater awareness of these relationships and were able to describe them with more detail than Novice Participants.

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Summary for Structural Knowledge

Problem-based learning environments need to accommodate the structural knowledge of learners so that interrelationships between entities within the problem domain can be considered during the process of resolving the problem. Situation analysis indicated that participants had structural knowledge as to the effects of movement speed and terrain inclination on physical exertion and self-rescuer oxygen consumption during emergency evacuations in the Challenger mine (Chapter 4.2.3). In order to accommodate this structural knowledge, these relationships were integrated within the problem domain where users' physical exertion and oxygen consumption increased in relation to their movement speed and the inclination of the terrain over which they were moving.

Findings elicited from the FUMES implementation indicated that, while both groups of participants identified relationships within the problem domain, Experienced Participants identified them more readily than Novice Participants. Both Experienced Participants and Novice Participants described the nature of the relationships between physical effort and movement, physical effort and breathing, and physical effort and oxygen consumption consistently, but the responses provided by Experienced Participants demonstrated a better understanding by virtue of the provision of greater descriptive detail.

This suggests that FUMES effectively accommodated the real world structural knowledge of participants, although this was more evident for Experienced Participants than Novice Participants. This was consistent with previous analysis (Chapter 7.2) which indicated that Experienced Participants were more effective at recognising the information needed for problem-solving activity in relation to that which was expressed in the problem, which is consistent with the application of structural knowledge (Lee, 2004).

This indicates the need to identify and accommodate the structural knowledge of users in order to support the construction and transfer of knowledge in 3D, problem-based learning environments. Analysis of the data collected during the FUMES implementation indicates the following findings in relation to the structural knowledge situational factor:

- Relationships between entities within the problem domain should be characterised in accordance with users' existing structural knowledge of the real world problem. In practice, this means that relationships within the problem domain should exhibit

behaviour that that is consistent with users' expectations, and;

- Draw explicit links between variables in order to assist users to identify relationships between concepts within the problem domain. Employing auditory or visual cues that may not be present in the real world problem scenario is one way of highlighting the nature of these relationships.

7.1.4 General Problem-solving Skills

General problem-solving skills are used in conjunction with existing domain specific knowledge to resolve problems and identify an appropriate problem-solving strategy, but are typically relied upon more heavily when such knowledge is lacking. Situation analysis established that the extent of general problem-solving skill possessed by participants could not be accurately determined and thus were not specifically factored into the design of the simulation environment (Chapter 4.2.4). Nevertheless, general problem-solving skills are important to the problem-solving process and should be accommodated within problem-based learning environments via the elicitation of domain specific knowledge.

The following sections detail the data analysis for general problem-solving skills as a means of determining the extent to which this Situational Analytical Factor was accommodated within FUMES. This was undertaken according to evaluation criteria established from the literature (Table 2.14) pertaining to reliance on general problem-solving skills and the specificity of the problem-solving strategy.

Reliance on General Problem-solving Skills

Two questionnaire prompts were used to identify the extent to which participants relied on their existing domain specific knowledge and general problem-solving skills, respectively (Figs. 7.4 and 7.5).

I relied on my knowledge of the Challenger mine and its emergency evacuation procedures to complete the training scenarios
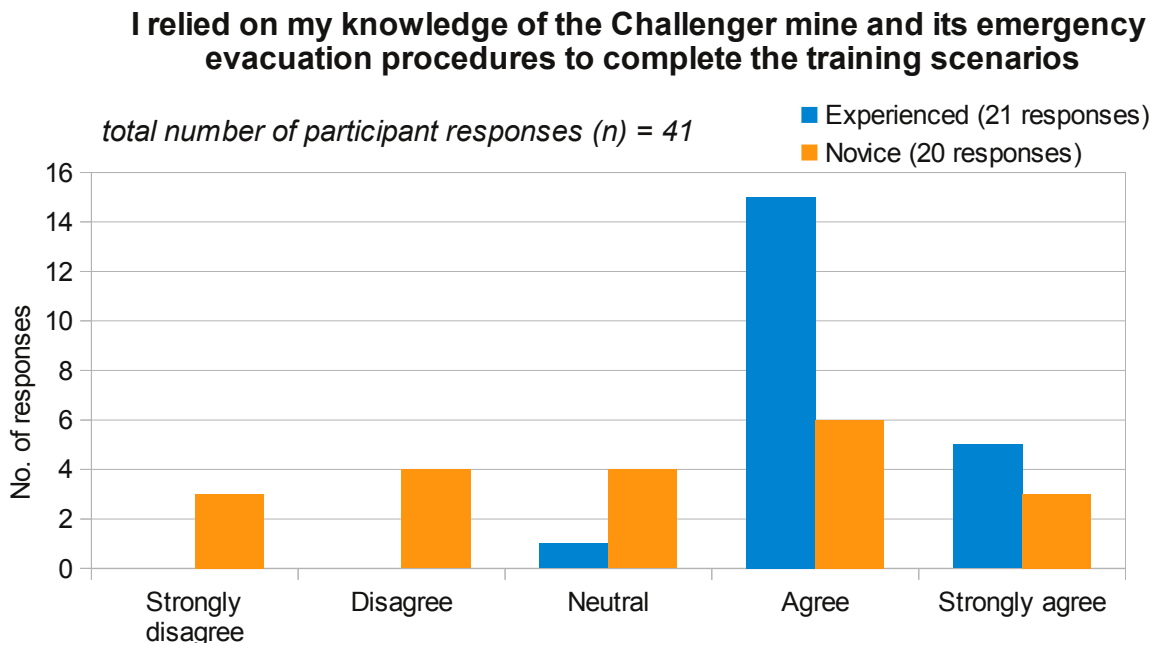
Figure 7.4. Reliance on existing knowledge of emergency evacuation procedures at Challenger

I relied on my general problem-solving skills to complete the training scenarios
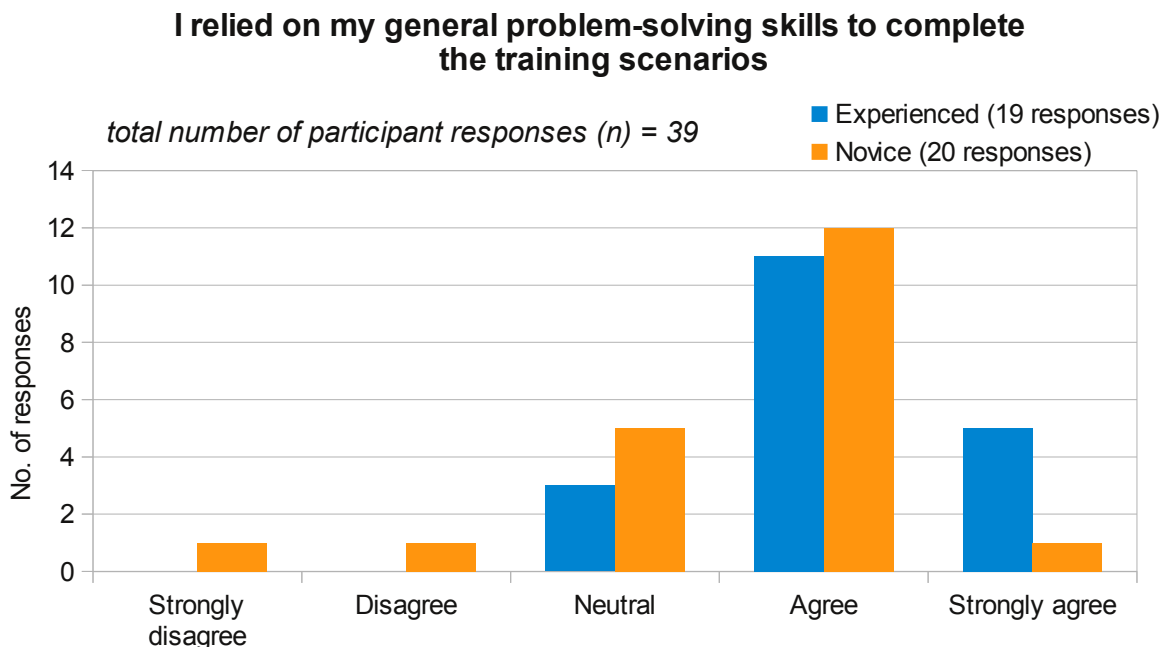
Figure 7.5. Reliance on general problem-solving skills

Experienced Participants relied on their existing domain specific knowledge to a greater extent than Novice Participants (Fig. 7.4). However, reliance on general problem-solving skills were

more equitable between experienced and Novice Participants (Fig. 7.5). This demonstrated that Experienced Participants relied on both their existing domain specific knowledge and general problem-solving skills, while Novice Participants were far more reliant on their general problem-solving skills.

Four Experienced Participants were also interviewed in relation to how their existing knowledge of emergency evacuations at Challenger affected their performance within the simulator. Responses from two of the Experienced Participants indicated that the problem-solving task in FUMES seemed familiar to them and that they had a good understanding of what they needed to do to achieve resolution:

- "... I knew what to do with the self-rescuer, knew that I had to get to a refuge chamber", and;
- "... you sort of know exactly what you've got to do, it sort of puts you into that autopilot sort of mode."

The remaining two Experienced Participants made comments to suggest that the simulation reflected the manner in which emergency evacuations were initiated within the real world mine, and that the simulation reinforced existing knowledge, which suggested that their existing knowledge served to familiarise themselves with the problem-solving task in FUMES.

Interview responses were also sought from three Novice Participants in relation to to how their existing knowledge of emergency evacuations at Challenger affected their performance within the simulator. While two of these Novice Participants were unable to respond to this question as their existing induction training was incomplete, the remaining Novice Participants did suggest that their experience at Challenger was of use during the first two problem-solving instances. This Novice Participant also indicated that experience at other underground mines was beneficial during problem-solving activity.

Thus, the questionnaire and interview responses suggested that Novice Participants were more reliant on general problem-solving skills than Experienced Participants due to an absence of existing domain specific knowledge. In contrast, Experienced Participants relied on their existing domain specific knowledge and general problem-solving skills more equitably. Experienced Participants indicated that their knowledge of emergency evacuation procedures at Challenger afforded them familiarity with the problem and the actions required for achieving

resolution.

Specificity of the Problem-solving Strategy

Four Experienced Participants and three Novice Participants were interviewed in relation to the specificity of the problem-solving strategy they used in FUMES. The responses from all four Experienced Participants indicated a clearly defined problem-solving strategy which utilised information acquired from within the virtual mining environment:

- "My general strategy was to confirm exactly what level I was at, that was my first thing, and I knew where the fire or the incident was at the time, so I assessed that, worked out exactly where I was, and by knowing exactly what level I was on, I could work out what escape way I could use, or walk down the decline."
- "The closest one. If I had to go up or down, it didn't bother me. I wasn't really concerned about I got there, I was quite prepared to walk up the decline rather than climb a ladder, whatever it was that was required. I wasn't really concerned about the emergency either, just it was an emergency and my response was to go to a refuge chamber."
- "The thing for me would be to move downhill to the nearest refuge chamber and not move into danger if I knew where it was and I could avoid it. So if I had to, for instance, get to a refuge chamber and I couldn't move along the drive I would then move for an escape way and bypass the obstruction"

These responses provided evidence to indicate the formulation of strong, domain specific strategies by Experienced Participants for achieving problem resolution in FUMES. Furthermore, they also suggested the application of general problem-solving procedures in the form of orientation, determining location and direction, and evaluating efficiency.

Interview responses from the three Novice Participants indicated the application of problem-solving strategies which were not as certain or directed as those employed by Experienced Participants. Two Novice Participants suggested that their problem-solving strategies were predominantly focussed on orientation within the virtual mine with little regard for other considerations:

- "Trying to orientate where I am to where I need to be … I just got completely twisted around and couldn't figure it out", and;
- "Look for signs really, especially if you knew the mine you'd be looking for signs."

Feedback provided by the third Novice Participant demonstrated a more cohesive strategy, stating that their aim was to get to the refuge chamber as quickly as they could using as little energy as possible. However, given that this Novice Participant was yet to tour the underground mine at Challenger and had no previous experience in underground mining, this suggested that they may have struggled to put this strategy into practice within FUMES. Thus, the feedback provided by Novice Participants indicated the application of weaker, less certain problem-solving strategies compared to their more experienced counterparts. However, interview responses from Novice Participants did provide evidence to suggest the application of general problem-solving procedures for the purposes of orientation, determining location and direction, and evaluating efficiency.

Observations made by the Training Staff Member at Challenger also provided insights. Experienced Participants demonstrated a clear understanding of how to resolve the problem-solving task within FUMES, while Novice Participants struggled with orientation and navigation within the virtual mine. Further observations indicated Novice Participants required considerable coaching in relation to the role of escape ways, refuge chambers, and self-rescuers during problem-solving activity. The Training Staff Member did note however, that Novice Participants who had experience at other underground mines were comparable to Experienced Participants in relation to the application of emergency evacuation procedure knowledge within FUMES.

The interview responses provided by participants and the Training Staff Member therefore suggested that Experienced Participants employed strong, domain specific strategies that utilised existing domain specific knowledge. In contrast, Novice Participants were seen to employ weaker problem-solving strategies as a result of a lack of existing knowledge that was specific to the problem domain. However, both groups of participants indicated the application of general problem-solving skills in relation to orientation, determining location and direction, and evaluating efficiency.

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Summary for General Problem-solving Skills

Learners utilise their general problem-solving skills in association with their knowledge of the problem domain to resolve problem-solving tasks within problem-based learning environments. While participants' general problem-solving skills were not specifically factored into the design of FUMES due to an inability to accurately quantify them during Situation Analysis (Chapter 4.2.4), the link between generalised problem-solving skills and contextualised problem-solving skills is clearly evident.

Findings elicited from the FUMES implementation demonstrated that Experienced Participants relied on both their existing domain specific knowledge and general problem-solving skills, whilst Novice Participants were far more reliant on their general problem-solving skills. This was attributed to a lack of existing domain specific knowledge regarding orientation and navigation within the Challenger mining environment on behalf of Novice Participants. This deficiency was reflected in participants' choice of problem-solving strategy, whereby Experienced Participants employed strong, domain specific strategies, whilst Novice Participants used weaker problem-solving strategies which were more fixated on trying to maintain locational awareness. Participants from both groups demonstrated the use of general problem-solving skills to orientate, determine location and direction, and evaluate efficiency, although these general problem-solving skills were utilised more effectively by Experienced Participants than Novice Participants (Chapters 7.1 and 7.2).

This suggested that FUMES effectively accommodated the general problem-solving skills of participants by eliciting existing domain specific knowledge. This was consistent with previous analysis which indicated that FUMES was more effective at accommodating existing domain specific knowledge for Experienced Participants than Novice Participants (Chapters 7.1, 7.2, and 7.3). As a result, Experienced Participants were able to make better use of general problems-solving skills to orientate, determine locations and directions, and evaluate efficiency, in addition to facilitating the identification of strong domain specific problem-solving strategies.

This indicates the need to identify and accommodate the general problem-solving skills of users in order to support the construction and transfer of knowledge in 3D, problem-based learning environments. Analysis of the data collected during the FUMES implementation indicates the following findings in relation to the general problem-solving skills situational factor:

- General problem-solving skills require domain specific knowledge to act upon. During design, this means that one should use contextually relevant problem-solving knowledge to promote the use of general problem-solving skills and provide users the freedom to utilise their knowledge experientially. As an example, a problem-solving task which was situated within the context of underwater maintenance on an oil platform using scuba equipment could be used to promote the use of general problem-solving skills such as time management.

- Any inadequacies in domain knowledge that may prevent the effective use of general problem-solving skills utilised towards the resolution of the problem need to be accommodated. In practice, this means that learning resources may need to be provided in order for users' to have the necessary knowledge of the problem domain to utilise their general problem-solving skills effectively. Users who knew nothing about semaphore could be provided with learning resources which detailed the various flag positions as a means of facilitating pattern recognition skills during a problem-solving task involving naval manoeuvres, for example.

7.1.5 Situatedness

Learning transfer requires learning within the simulation environment to be situated within the activity, context and culture in which it is developed and used within the real world environment. Situation analysis established that evacuating the Challenger mine during an emergency was a highly contextualised activity. Personnel were required to traverse the mining environment to reach a refuge chamber in accordance with the established emergency evacuation procedure used at Challenger (Chapter 4.2.5). This process required personnel to determine an appropriate route to refuge given their initial location and proximity to environmental hazards whilst also considering physical exertion in order to preserve the oxygen supply in their self-rescuer, which was to be used if smoke was encountered.

The following sections detail the data analysis for situatedness as a means of determining the extent to which this Situational Analytical Factor was accommodated within FUMES. This was undertaken according to evaluation criterion established from the literature (Table 2.14) pertaining to situatedness relative to the real world problem.

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Situatedness Relative to the Real World Problem

Experienced Participants were surveyed to gauge the situatedness of problem-solving activity in FUMES with respect to emergency evacuations in the Challenger mining environment (Figs. 7.6 through 7.9).

The training scenarios effectively represented real world emergency evacuations at Challenger
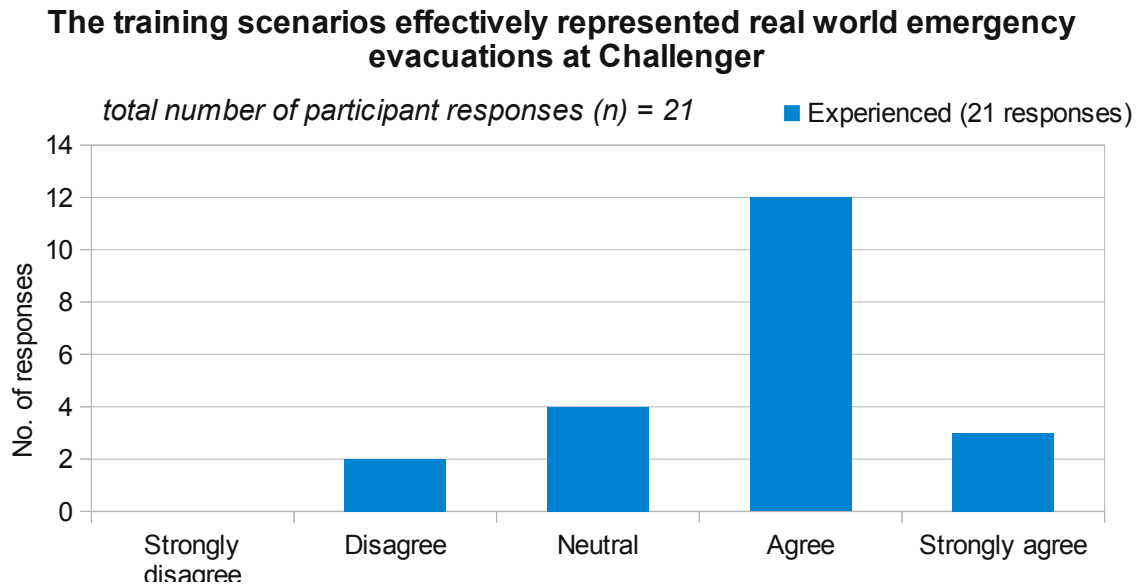
Figure 7.6. Effectiveness with which the problem-solving task represented emergency evacuations at Challenger

Obstacles in the training scenarios were consistent with real world emergency evacuations at Challenger

total number of participant responses (n) = 21   ■ Experienced (21 responses)
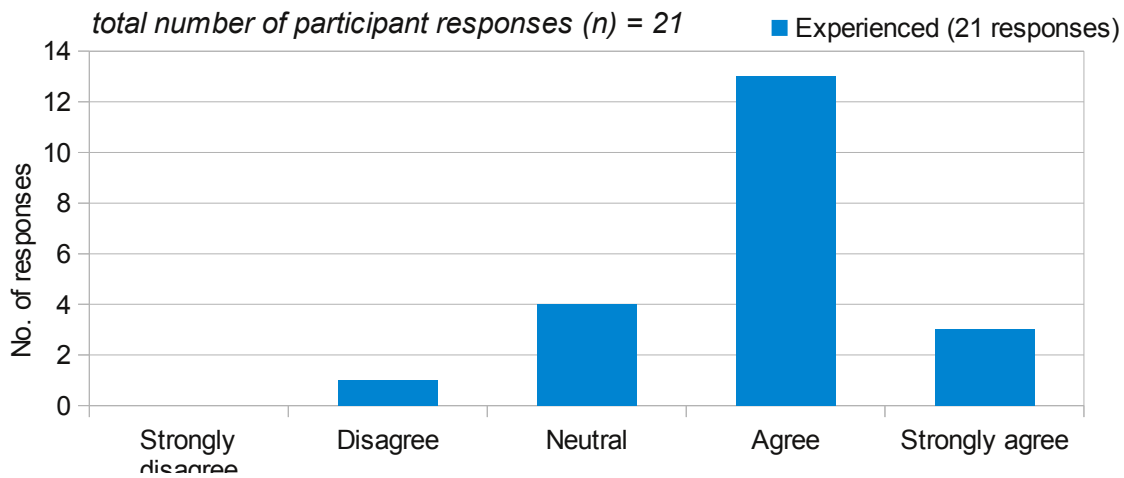
Figure 7.7. Consistency with which the problem-solving task represented the obstacles present during emergency evacuations at Challenger.

I had to consider the same things during the training scenarios that I would during a real world emergency evacuation at Challenge

total number of participant responses (n) = 21   ■ Experienced (21 responses)
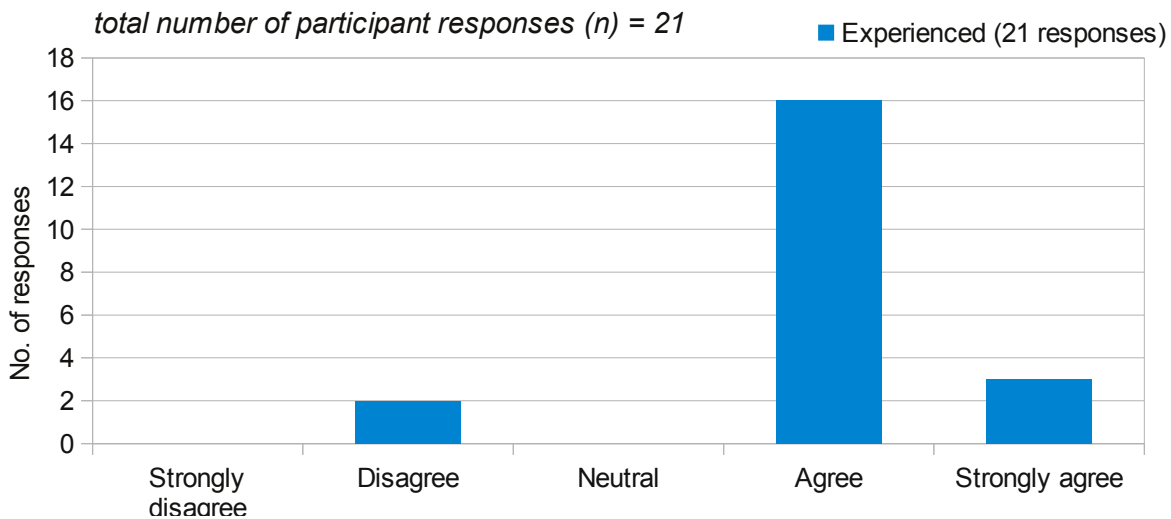
Figure 7.8. Extent to which the problem-solving task embodied the same concerns as emergency evacuations at Challenger

The behaviour of the self-rescuer and cap lamp were consistent with real world emergency evacuations at Challenger
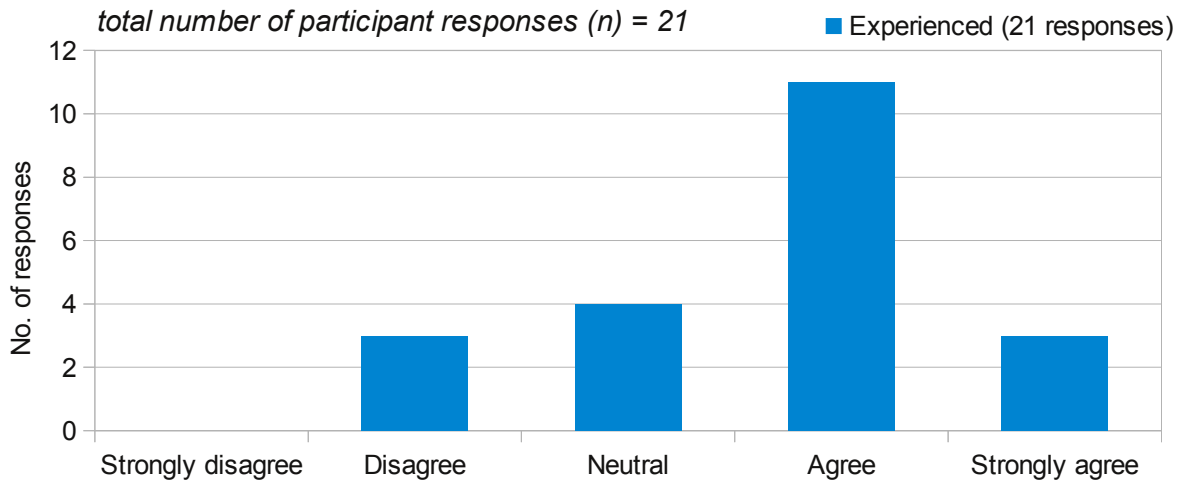
Figure 7.9. Extent to which the behaviour of the cap lamp and self-rescuer was consistent with emergency evacuations at Challenger

Experienced Participants indicated that the problem-solving task effectively represented emergency evacuation procedures in the Challenger mine (Fig. 7.6) and needed to overcome similar obstacles (Fig. 7.7) and observe the same considerations (Fig. 7.8) that they would in the real world environment. Furthermore, the behaviour of the cap lamp and self-rescuer within the simulation environment were deemed to be consistent with their real world counterparts during an emergency evacuation at Challenger (Fig. 7.9).

Collectively, the questionnaire responses demonstrated problem-solving activity in FUMES was well situated with respect to emergency evacuation procedures in the Challenger mining environment. Experienced Participants indicated that the problem-solving task in FUMES effectively represented a real world emergency evacuation in the Challenger mine and faithfully embodied the obstacles, considerations, and behaviours of the cap lamp and self-rescuer in this regard.

Summary for Situatedness

To encourage the transfer of learning, the problem-solving task within problem-based learning environments needs to be well situated in relation to existing problem-solving experience.

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Situation analysis indicated that the real world problem was highly contextualised as it called upon procedures specific to emergency evacuation scenarios within the Challenger mining environment (Chapter 4.2.5). In order to accommodate the situatedness of the real world problem, problem-solving activity was established within a scale, 3D representation of the Challenger mine, where users were required to overcome environmental obstacles on their way to reaching a refuge chamber whilst managing the supply of oxygen in their self-rescuer in accordance with established real world protocols.

Findings elicited from the FUMES implementation demonstrated that problem-solving activity within FUMES was effectively situated with respect to emergency evacuations in the Challenger mining environment. Experienced Participants indicated that the problem-solving task effectively represented emergency evacuations in the Challenger mine such that they needed to overcome similar obstacles and observe the same considerations in order to achieve resolution. The behaviour of the cap lamp and self-rescuer within the simulation environment was also deemed to be consistent with their real world counterparts during an emergency evacuation.

This suggests that FUMES effectively accommodated the situatedness of the real world problem at Challenger. As such, Experienced Participants were able to employ strong, domain specific problem-solving strategies which utilised existing domain specific knowledge pertaining to emergency evacuations of the Challenger mine (Chapters 7.1.2 and 7.1.4).

Analysis of the data collected from the FUMES implementation indicates the need to identify and accommodate the situatedness of the problem-solving task in order to support the construction and transfer of knowledge in 3D, problem-based learning environments. Analysis of the data collected during the FUMES implementation indicates the following findings in relation to the situatedness situational factor:

- The problem-solving task needs to be situated with respect to both the context and activity of the real world problem in order to facilitate the transfer of learning. This means that the problem-solving task should present users with similar obstacles and considerations within a familiar context such that the method for resolution can be directly applied to the real world problem.

7.1.6 3D Representation

The ability to represent objects and environments three-dimensionally allows 3D simulation

environments to construct scale representations of real world spaces which faithfully embody dimensions, perspective and relative distances. Situation analysis identified the important spatial characteristics of the real world mine that needed to be represented accurately within the virtual counterpart (Chapter 4.2.6). These included the layout and structure of the mine, the locations of refuge chambers and escape rises, and the visual cues that assisted orientation and navigation.

The following sections detail data analysis for 3D representation as a means of determining the extent to which this Situational Analytical Factor was accommodated within FUMES. This was undertaken according to evaluation criteria established from the literature (Table 2.14) pertaining to the three-dimensional representation of the environment, and the extent to which knowledge was effectively conveyed.

Three-dimensional Representation of the Environment

A series of questionnaire prompts were presented to Experienced Participants and Novice Participants regarding the 3D representation of the virtual mining environment. These responses are depicted in Figures 7.10 through 7.12 as follows:
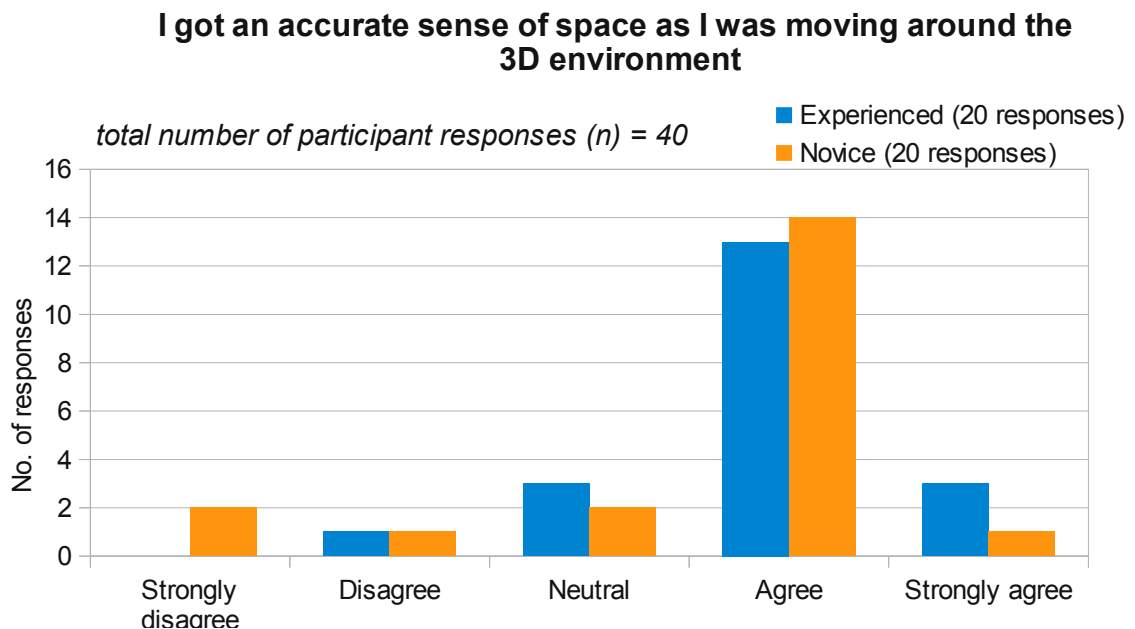
Figure 7.10. Sense of space within the 3D environment

The size and scale of the mine was represented accurately by the 3D environment

total number of participant responses (n) = 40

■ Experienced (20 responses)
■ Novice (20 responses)
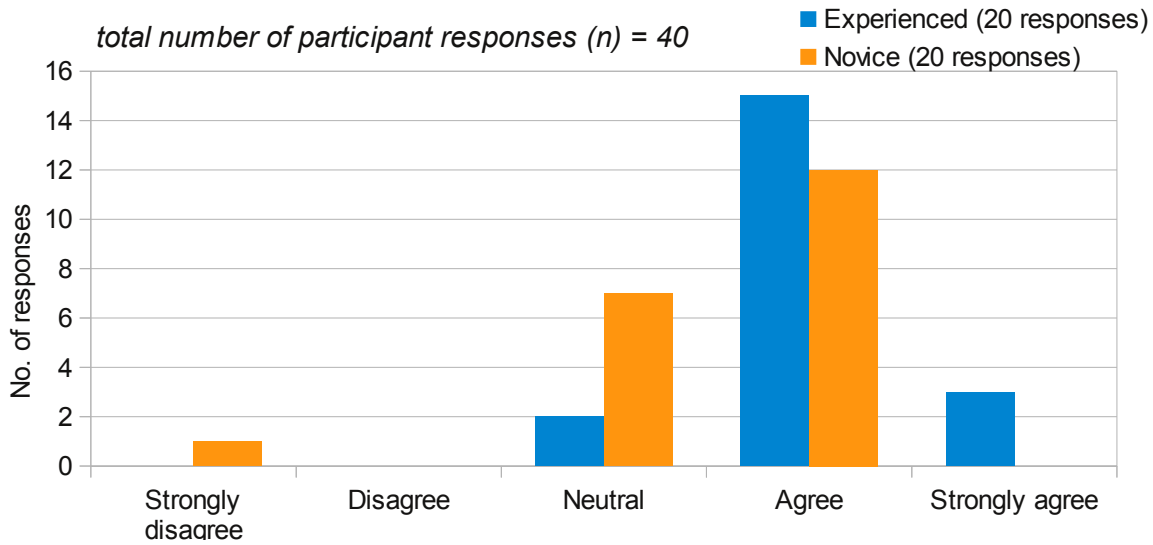
Figure 7.11. Accuracy of the size and scale of the virtual mine in relation to the real world mine

I knew whether I was moving uphill, downhill, or on a level surface within the 3D environment

total number of participant responses (n) = 40

■ Experienced (20 responses)
■ Novice (20 responses)
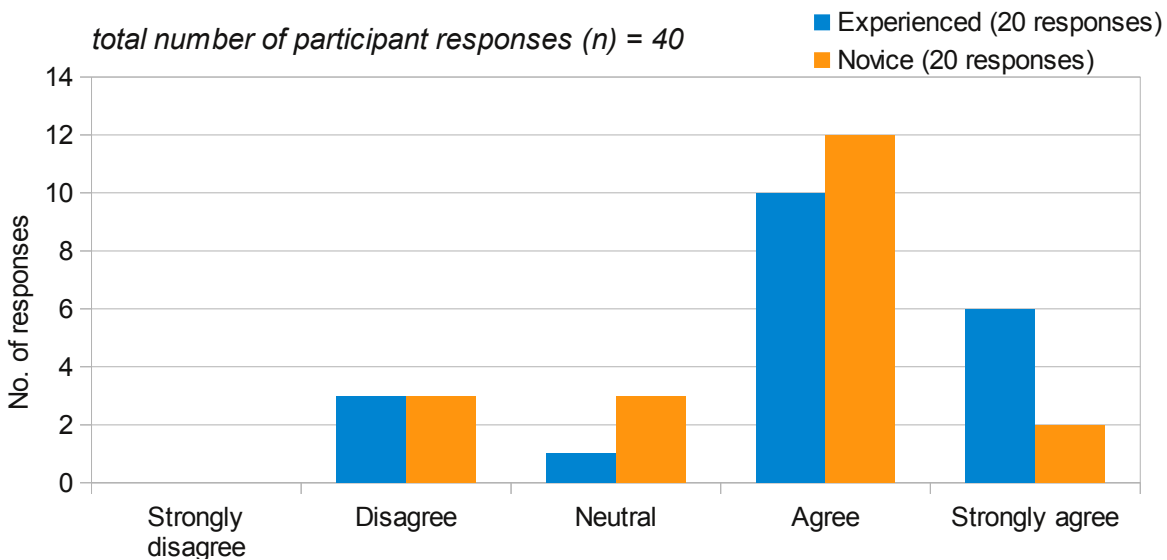
Figure 7.12. Awareness of the inclination of the terrain during movement within the virtual

mine

Both Experienced Participants and Novice Participants had an accurate sense of space as they

moved through the virtual mine (Fig. 7.10), and could determine the inclination of the terrain as they moved over it (Fig. 7.11). However, Experienced Participants indicated that they were more confident that the size and scale of the Challenger mine was represented accurately than Novice Participants (Fig. 7.12).

These responses collectively demonstrated that the virtual mine effectively represented three-dimensionally such that participants had an accurate sense of space and were aware of the inclination of the terrain as they moved through the environment. The size and the scale of the virtual mine was deemed to be consistent with that of the real world counterpart, particularly by Experienced Participants who had greater familiarity with this environment.

Extent to which Knowledge is Effectively Communicated

Experienced Participants and Novice Participants were queried via questionnaire and interview regarding the effectiveness with which knowledge was communicated by the 3D environment. Questionnaire prompts were used to evaluate the dissemination of locational knowledge (Figs. 7.13 and 7.14), behavioural knowledge (Figs. 7.15 and 7.16), structural knowledge (Figs. 7.17 and 7.18), and procedural knowledge (Fig. 7.19), each of which was important in relation to accurate representation of the Challenger mining environment during an emergency evacuation scenario.
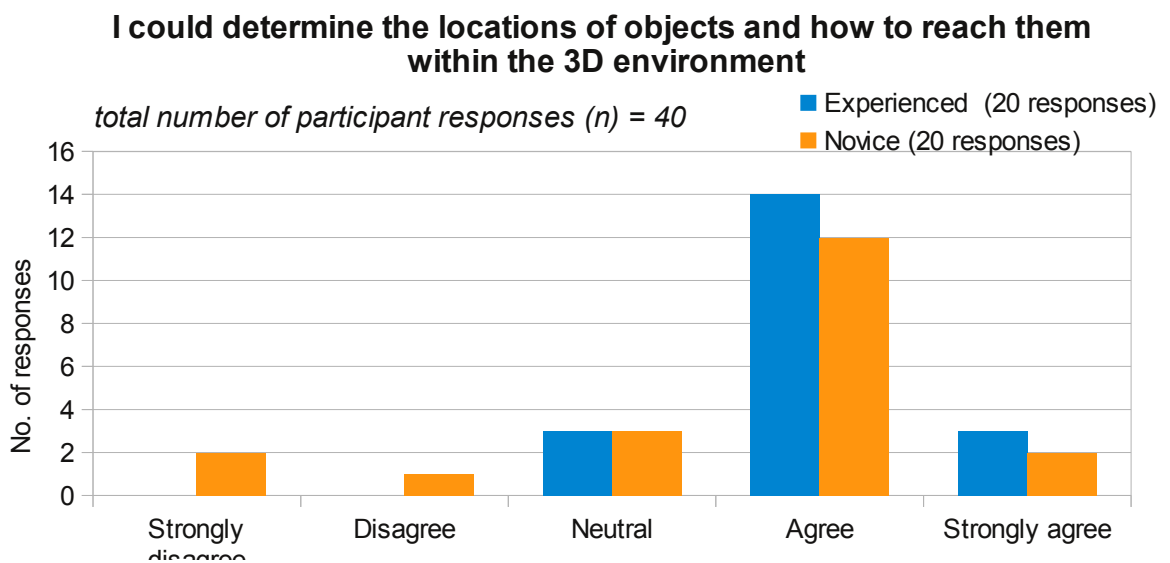
Figure 7.13. Effectiveness with which objects could be located within the virtual mine

I had a clear sense of my location within the 3D environment
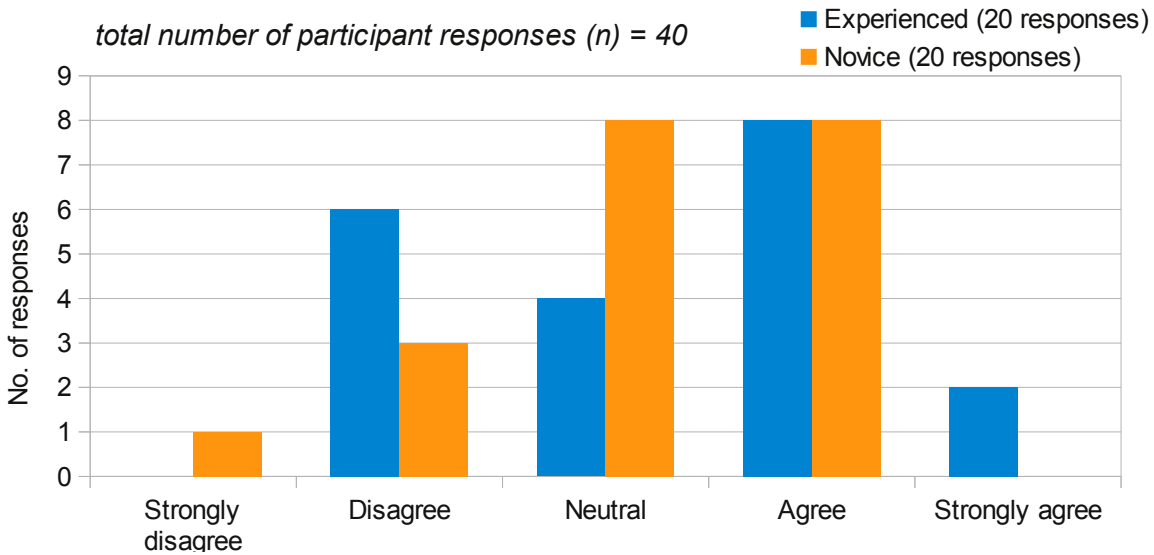
Figure 7.14. Effectiveness with which a clear sense of location could be determined within the virtual mine

I knew when and where to use my self-rescuer within the 3D environment
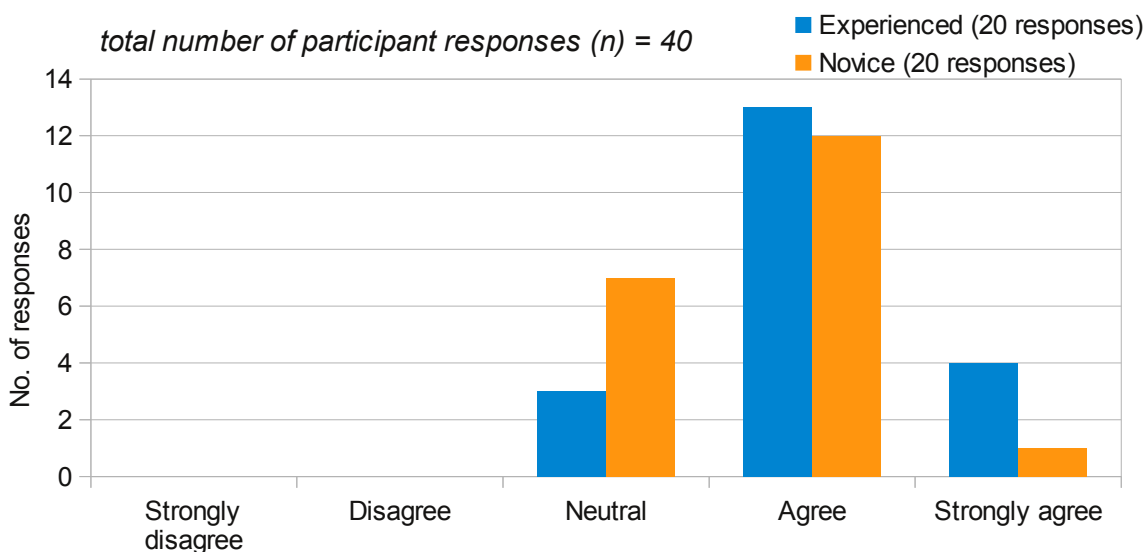
Figure 7.15. Effectiveness with which appropriate circumstances for self-rescuer usage could be identified within the virtual mine

**I knew when and where to use an escape rise within
the 3D environment**
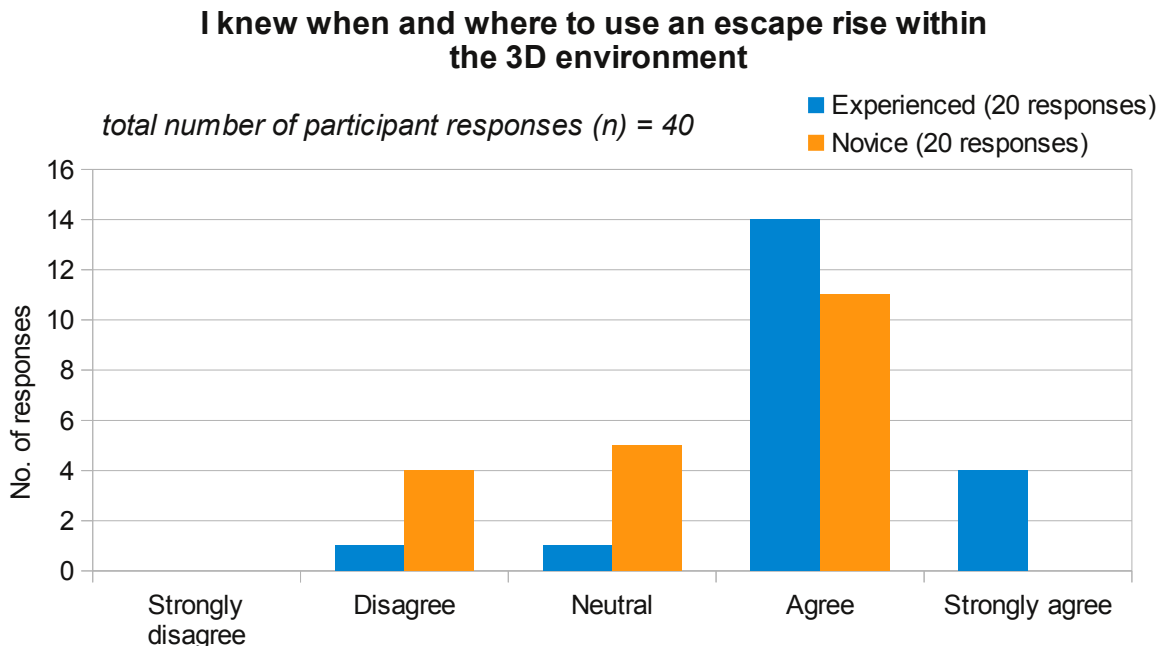
Figure 7.16. Effectiveness with which appropriate circumstances for escape rise usage could be determined within the virtual mine

**The physical effort I expended within the simulation was affected
by the slope of the terrain**
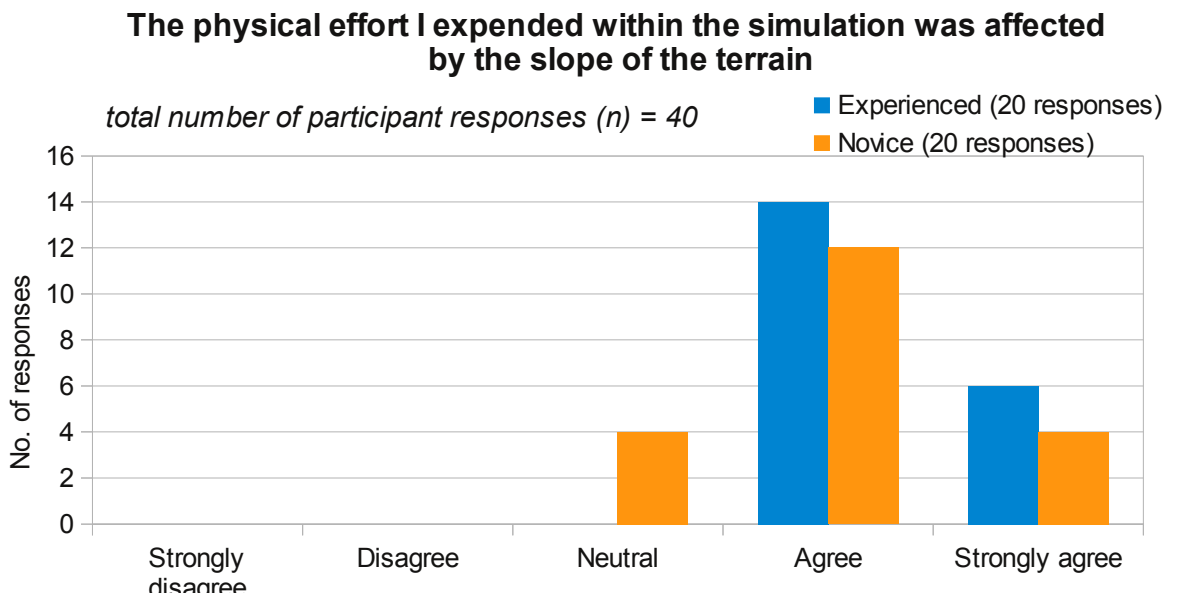
Figure 7.17. Relationship between terrain slope and physical effort expenditure

The physical effort I expended within the simulation affected the rate at which the oxygen in my self-rescuer was used
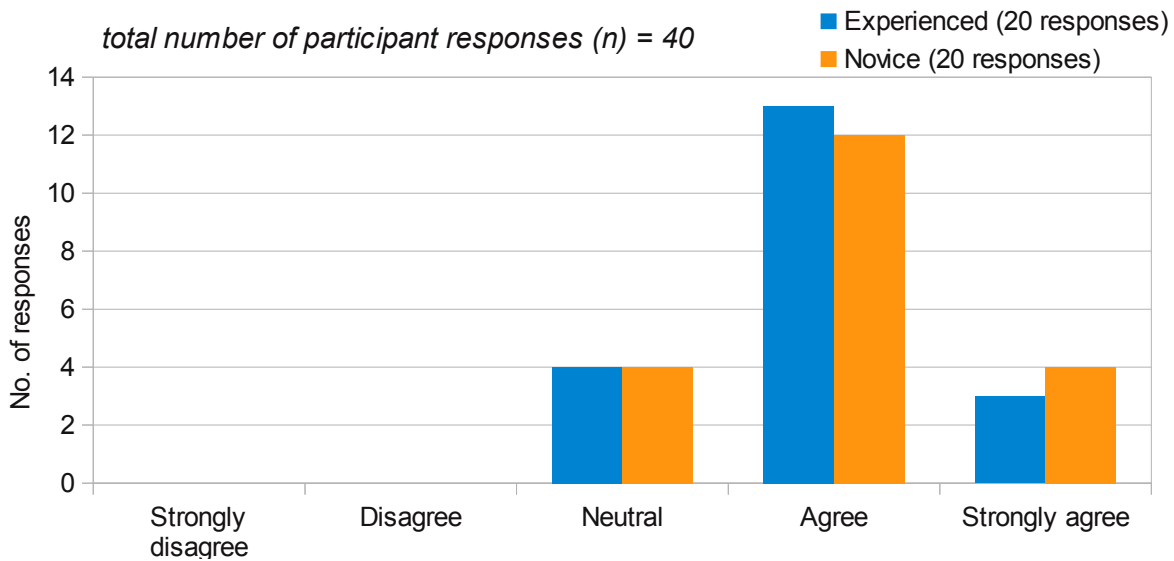
Figure 7.18. Relationship between physical effort expenditure and self-rescuer oxygen

consumption

The training scenarios provided a clear understanding as to correct evacuation procedure during an emergency
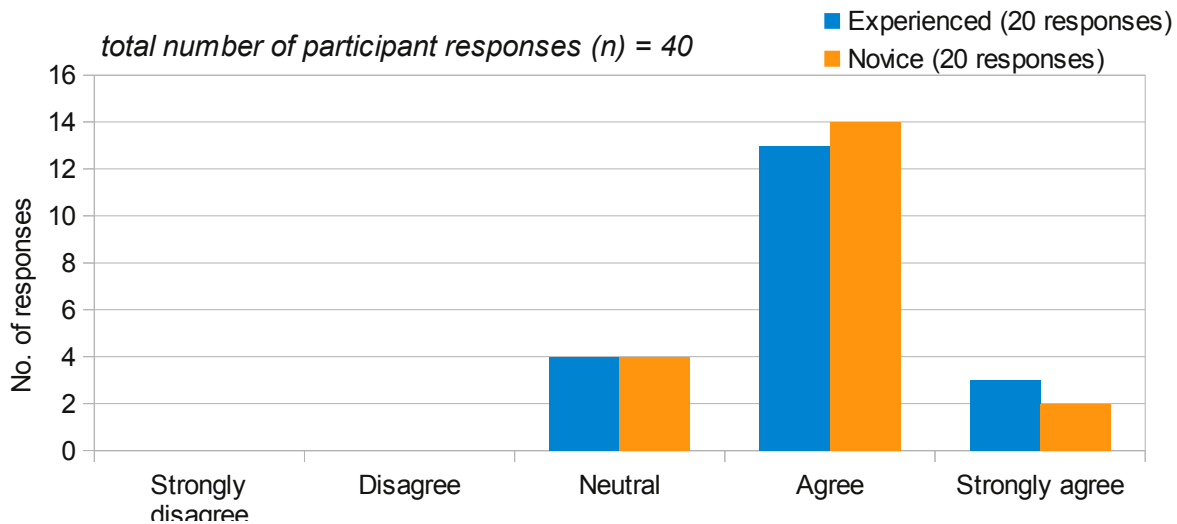
Figure 7.19. Extent to which problem-solving activity within the 3D simulation environment

reflected correct emergency evacuation procedure

The 3D representation effectively imparted locational knowledge so participants could

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determine a route between their current position and a given object once it had been sighted (Fig. 7.13). It was comparatively less effective at conveying locational knowledge which could be used to maintain awareness of participants' location (Fig. 7.14). This was consistent with previous analysis which indicated that an absence of adequately represented spatial cues, specifically vent bags and other mining infrastructure, had a negative impact on participants' ability to orientate and navigate within the virtual mine (Chapter 6.1.2).

Behavioural knowledge was adequately conveyed regarding the use of self-rescuers (Fig. 7.15) and escape rises (Fig 7.16). This suggests that three-dimensional representation afforded participants the ability to determine their proximity to environmental hazards such as fire and smoke and determine the use of escape rises and their self-rescuer accordingly, although this was more evident for Experienced Participants than Novice Participants.

Structural knowledge was well communicated regarding the relationship between terrain inclination and physical effort expenditure (Figs. 7.17), and physical effort expenditure and self-rescuer oxygen consumption (Fig. 7.18). This suggests that the 3D environment adequately represented terrain inclination where participants could identify when they were moving up or down the decline and in turn associate this with feedback that represented their physical effort expenditure. This further demonstrates that the dynamic and experiential nature of the 3D environment afforded participants the ability to continually appraise their self-rescuer oxygen consumption based on their physical effort expenditure.

The 3D environment effectively imparted structural knowledge such that participants associated the inclination of the terrain with physical exertion (Fig. 7.17), and physical exertion with self-rescuer oxygen consumption (Fig. 7.18). Interview responses from four Experienced Participants and three Novice Participants attributed this to the experiential and dynamic nature of activity within the 3D environment:

- " You did get an impression that if you moved faster you were going to, you heard the breathing going faster and that sort of a thing so you did actually realise you were chewing your air up a little bit more";
- " … you can hear yourself breathing in the self-rescuer and you can hear your breathing getting a lot more laboured when you've been running or walking a lot … ";
- " … You've got the heavy breathing within the scenario and you can see the changes in slope";

- " When you were climbing up a ladder you could hear yourself breathing really heavy and things like that … ", and;
- " You knew like when you were, well you couldn't run, but it would tell that your breathing, you could hear your breathing was different and what not and you were moving a bit slower."

Procedural knowledge was also communicated adequately in relation to the correct evacuation procedure to use during an emergency (Fig. 7.19). Interview responses from four Experienced Participants and three Novice Participants in relation to the value of FUMES as a platform for emergency evacuation training suggests that this was the result of the experiential and dynamic nature of the 3D environment in which problem-solving activity was situated:

- "It gave me an idea, as I said I've never been underground before, where things would be and where you have to go.";
- "I rate it highly. With it's ability to take what you learn on paper and apply it in a practical sense. ";
- " … you can do your mock emergencies and everything else, but a simulation like this one, it's just so easy and it makes you think about a lot of things. Gets your mind on a lot of things as to what you should do and shouldn't do.", and;
- " … it's a good reminder just in the very basics like walking down to a refuge chambers and that sort of thing. So you do have to stop and think what you're supposed to be doing in order to get through the simulation."

Collectively, the questionnaire and interview prompts demonstrated that knowledge was imparted
as a result of situating problem-solving activity within a dynamic, three-dimensional representation of the Challenger mining environment. The three-dimensional representation afforded the dissemination of locational, behavioural, structural, and procedural knowledge as participants moved and interacted within the virtual mining environment.

Summary for 3D Environments

Problem-based learning can utilise 3D environments to accommodate the three dimensional characteristics of real world problem spaces for the purposes of providing a realistic depiction of real world problem-solving activity. Situation analysis identified the layout and structure of the

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Challenger mine, including the visual cues which aided navigation and the locations of escape rises and refuge chambers, as the key 3D characteristics of the environment in which the real world problem was situated (Chapter 4.2.6). In order to accommodate these characteristics, the 3D representation of the Challenger mine was modelled using real world planning diagrams so that spatial representations derived in the real world environment would be applicable within the virtual counterpart, and vice versa.

Findings elicited from the FUMES implementation demonstrated that the 3D environment provided an effective three-dimensional representation of the mine in which the dynamic and experiential nature of activity facilitated the effective conveyance of knowledge. Participants had an accurate sense of space and were aware of the inclination of the terrain as they moved through the environment. The size and the scale of the virtual mine was deemed to be consistent with that of the real world counterpart, particularly by Experienced Participants who had greater familiarity within this space. The 3D environment effectively conveyed locational knowledge, allowing participants to locate and reach objects within the virtual mine, but was less consistent in providing participants with a clear idea as to their location. Participants from both groups also indicated that the 3D environment disseminated behavioural knowledge regarding the purpose of the self-rescuer and escape rise during problem-solving activity, although this was more evident for Experienced Participants than those in Novice Participants. Structural knowledge was effectively conveyed such that participants were aware of the relationships between terrain inclination, physical exertion, and self-rescuer oxygen consumption, whilst the dissemination of procedural knowledge provided participants with a clear understanding as to correct evacuation procedure during an emergency.

This suggests that FUMES effectively accommodated the 3D characteristics of the Challenger mining environment. The ability to move, orientate, and interact freely within the 3D environment reflected the experiential nature of the real world problem scenario and was key to the acquisition of locational, behavioural, structural, and procedural knowledge. However, the inconsistency with which participants were able to maintain awareness of their location demonstrates that vent bags and servicing infrastructure within the virtual mine were not represented with sufficient fidelity to facilitate orientation and navigation (Chapter 6.1.2). This was a significant shortcoming, as the established learning objectives (Table 4.5) dictated that participants needed to be able to orientate themselves and navigate effectively in order to affect successful evacuation during a real world emergency. While vent bags and servicing infrastructure were identified as key spatial cues during situation analysis, the extent to which

personnel relied upon them to navigate within the mining environment was not fully appreciated. As such, their implementation was not afforded adequate priority due to the time constraints imposed by the study (Chapter 5.24).

This indicates the need to identify and accommodate the key 3D characteristics of the real world environment in which the problem is situated in order to support the construction and transfer of knowledge in 3D, problem-based learning environments. Analysis of the data collected during the FUMES implementation indicates the following findings in relation to the 3D representation situational factor:

- The physical characteristics of the real world environment that relate to the resolution of the problem require adequate 3D representation so that they can be recognised and utilised by users to achieve problem resolution. In practice, this means that these characteristics need to be identified and represented with sufficient fidelity, both in terms of the richness of visual detail and three-dimensional properties such as scale, dimensions, and position.

7.1.7 Immediate System Response

Immediate system response is necessary to provide the illusion of free movement and interaction within the virtual environment in a manner that is consistent with real world, three-dimensional space. Situation analysis identifies the user activity to which FUMES needed to provide immediate response to this end, comprising movement, orientation, climbing an escape rise, equipping the self-rescuer, and changing the beam setting on the cap lamp (Chapter 4.2.7).

The following sections detail the data analysis for immediate system response as a means of determining the extent to which this Situational Analytical Factor was accommodated within FUMES. This was undertaken according to evaluation criteria established from the literature (Table 2.14) pertaining to the perceived immediacy of system response to input, the consistency of frame rate, and the perceived sense of presence.

Perceived Immediacy of System Response to Input

Experienced Participants and Novice Participants were queried via questionnaire in order to

ascertain the perceived immediacy of system response in relation to mouse and keyboard input (Fig. 7.20).

The 3D environment responded immediately to my mouse and keyboard input
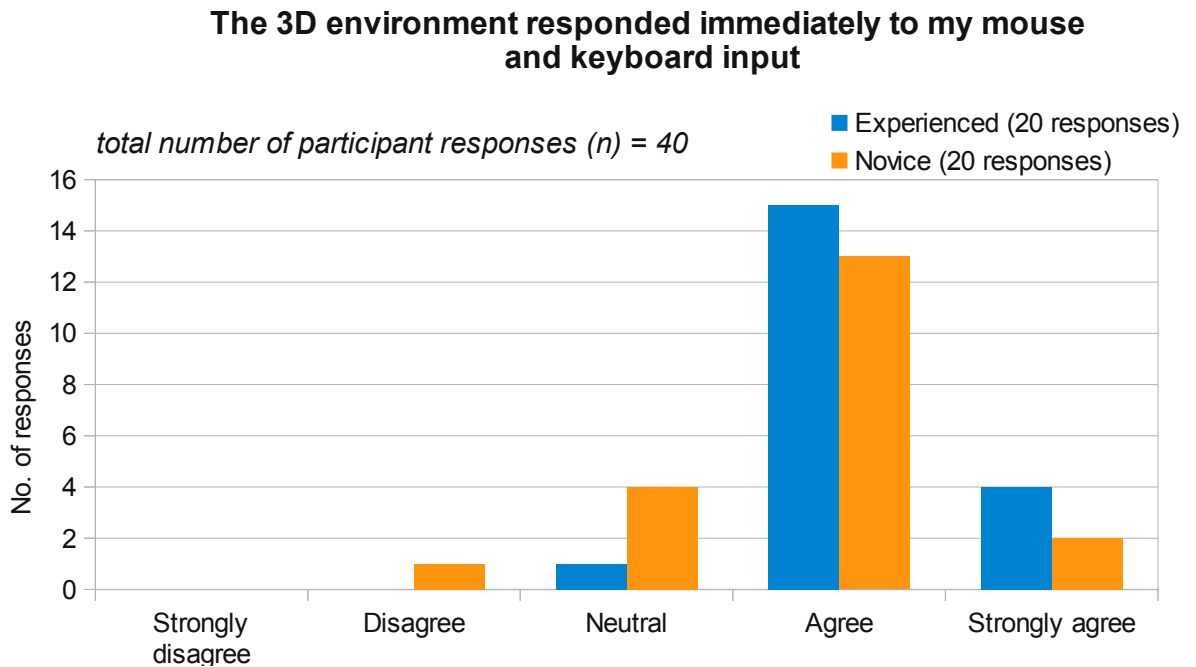
Figure 7.20. Immediacy with which the 3D simulation environment responded to user input

Both Experienced Participants and Novice Participants indicated that FUMES consistently responded to their mouse and keyboard input in an immediate manner (Fig. 7.20).

Consistency of Frame Rate

Questionnaire prompts were employed using Experienced Participants and Novice Participants to ascertain frame rate consistency as a measure of the immediacy of system response (Fig. 7.21).

The 3D environment displayed smoothly and seamlessly
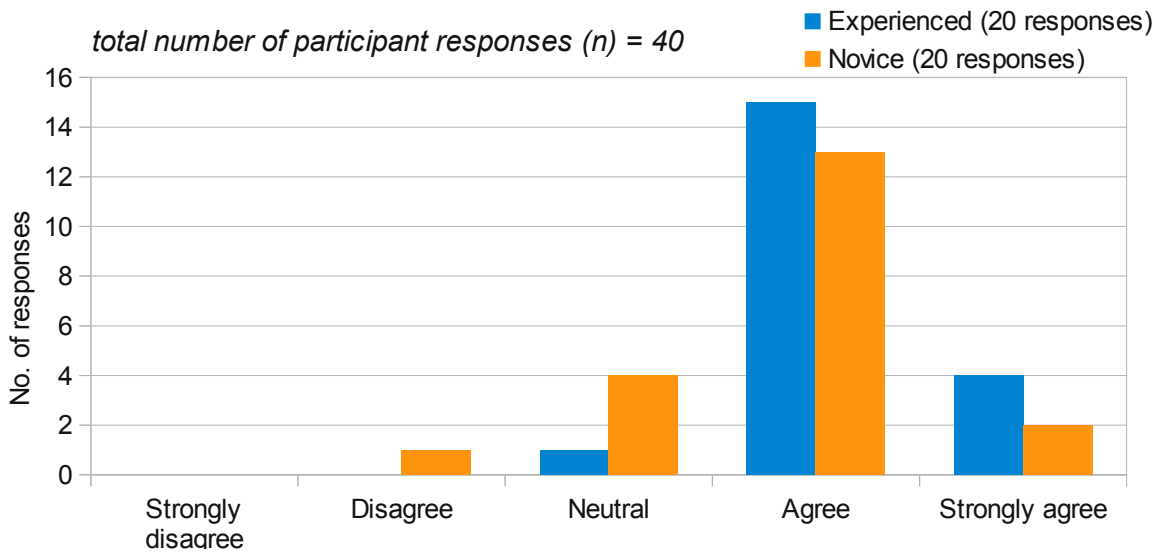
Figure 7.21. Smoothness and seamlessness of display within the 3D simulation environment

The visual feedback provided to participants within the 3D simulation environment was smooth and seamless (Fig. 7.21). This was consistent with performance measures indicating that the frame rate in FUMES was above thirty frames per second at all times, which exceeded the minimum fifteen to twenty frames per second required to provide a smooth and interactive experience ((Dalgarno et al., 2002; Farrell et al., 2003).

Thus, the questionnaire responses and frame rate performance measures demonstrate that both Experienced Participants and Novice Participants were provided with smooth and seamless visual display which was always above thirty frames per second.

Perceived Sense of Presence

Questionnaire responses were employed in order to gauge the extent to which Experienced Participants and Novice Participants felt that they had a presence within the virtual mining environment (Fig. 7.22).

**I felt as though I was physically present within
the 3D environment**
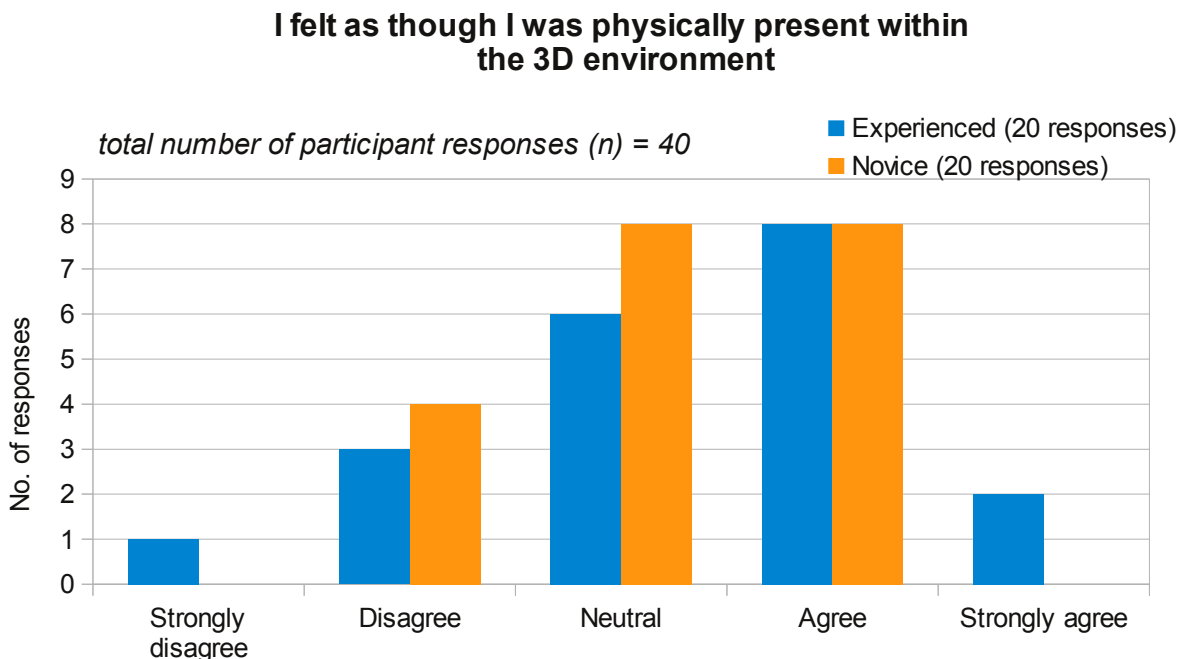
Figure 7.22. Perception of presence within the 3D simulation environment

The diversity in responses suggest that the virtual mining environment did not engender a sense of presence amongst participants consistently (Fig. 7.22).

Four Experienced Participants and three Novice Participants were interviewed to determine if they felt they had a physical presence within the virtual mine. The interview feedback reflected the variety of responses seen in the questionnaire (Fig. 7.22):

- "It does, you start getting, you feel like you're in suspense kind of thing … but, you still know you're in a simulation";
- "I knew I was at the computer but I was trying to picture like that is what it would be like underground";
- "It is still pretty easy to tell it is a computer game", and;
- "Pretty obvious I was sitting behind a computer"

However, one Experienced Participant did provide feedback during interview to suggest that the ability to move and interact effectively within the virtual mining environment contributed to their perception of presence:

- "You actually did get the impression that you were moving through, like you could actually move to areas that you wanted to go to. So yeah, without being silly about it, yes, you did get the impression that you were actually there and moving through the mine."

Analysis of the questionnaire and interview responses thus indicated that participants did not perceive a clear or persistent sense of presence within the virtual mining environment. However, feedback provided by one Experienced Participant during interview did indicate that the ability to move freely within the virtual mine contributed to a feeling of presence.

Summary for Immediate System Response

3D simulation environments that exist within a problem-based learning pedagogy need to provide continuous and immediate responses to user interaction in order to accommodate the experiential and dynamic nature of real world problem-solving activity. Situation analysis indicated that FUMES needed to provide users with immediate feedback in response to movement, orientation, climbing escape rises, and operation of the cap-lamp and self-rescuer in order to reflect the actions undertaken by personnel at Challenger during an emergency evacuation of the mine (Chapter 4.2.7). Accommodating these design characteristics required perceivable responses to be provided by FUMES in an immediate manner using an appropriately selected hardware platform that was technically capable in this regard.

Findings elicited from the FUMES implementation regarding the perceived immediacy of system response, the consistency of frame rate, and the perceived sense of presence indicated that FUMES responded with sufficient immediacy to facilitate effective interaction. FUMES provided visual feedback which updated smoothly and seamlessly in response to participant input at a frame rate that always exceeded thirty frames per second. However, responses suggested that the immediate system response alone was not sufficient to engender a strong sense of presence consistently amongst participants. Collectively, these findings suggested that FUMES provided an immediate response to participant input where a realistic sense of movement and interaction was accommodated within the virtual mine.

This indicates the need to identify the actions used to resolve the real world problem and accommodate them with immediate system response in order to support the construction and transfer of knowledge in 3D, problem-based learning environments. Analysis of the data

collected during the FUMES implementation indicates the following findings in relation to the immediate system response situational factor:

- User interaction which approximates the actions used to resolve the real world problem needs to be responded to immediately in order to reflect the experiential nature of real world activity. This entails selecting a hardware platform that effectively matches the software requirements so that full screen, full motion responses can be provided with sufficient immediacy and regularity, and;
- The frame rate needs to consistently meet or exceed thirty frames per second in order for system responses to user interaction to appear immediate, smooth, and seamless. In practice, this means that the computer hardware needs to be technically capable of providing perceivable responses at this frame rate at all times.

7.1.8 Authenticity of the Simulation Environment

Simulation environments attempt to authentically represent the appearance and behaviour of real world environments such that knowledge that is accumulated in one can be utilised in the other. Situation analysis established the physical and functional aspects of the real world environment that required authentic representation in order to facilitate the transfer of knowledge. These aspects encompass the physical depiction of the Challenger mining environment, including refuge chambers, escape rises, and environmental conditions, and behavioural concepts relating to movement speed, terrain inclination, physical exertion, self-rescuer and cap-lamp battery depletion, and the spread of smoke (Chapter 4.2.8).

The following sections detail the data analysis for the authenticity of the simulation environment as a means of determining the extent to which this Situational Analytical Factor was accommodated within FUMES. This was undertaken according to evaluation criteria established from the literature (Table 2.14) pertaining to physical fidelity and functional fidelity.

Physical Fidelity

Given their familiarity with emergency evacuation procedures at Challenger, Experienced Participants were asked to assess the physical fidelity of the virtual mine compared to the real world counterpart (Figs. 7.23 through 7.25).

Obstacles in the training scenarios were consistent with real world emergency evacuations at Challenger
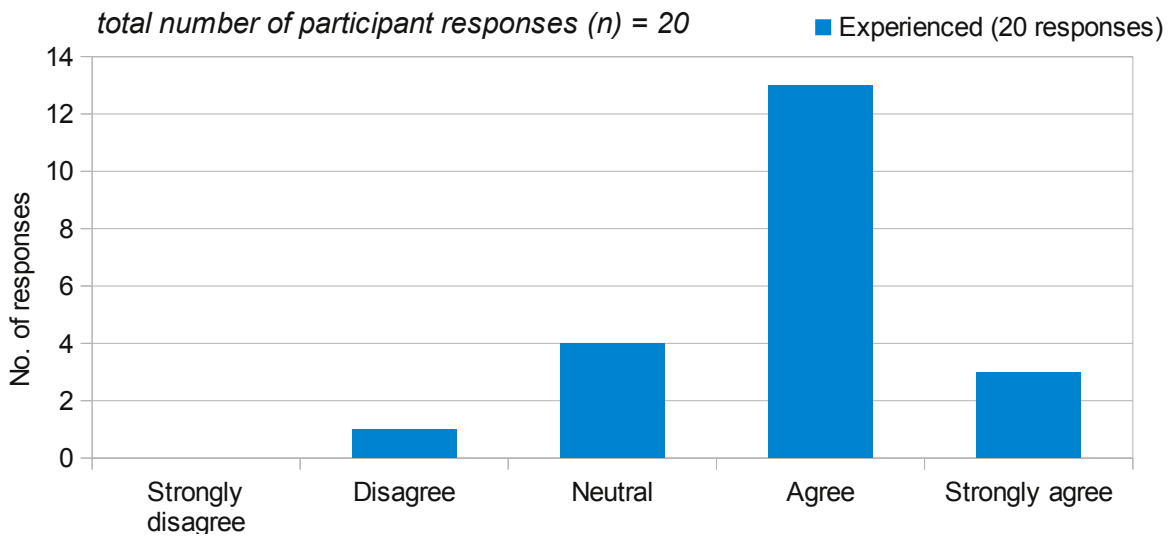
Figure 7.23. Consistency of obstacles during problem-solving activity in relation to real world emergency evacuations at Challenger

The simulation accurately represented the Challenger mining environment
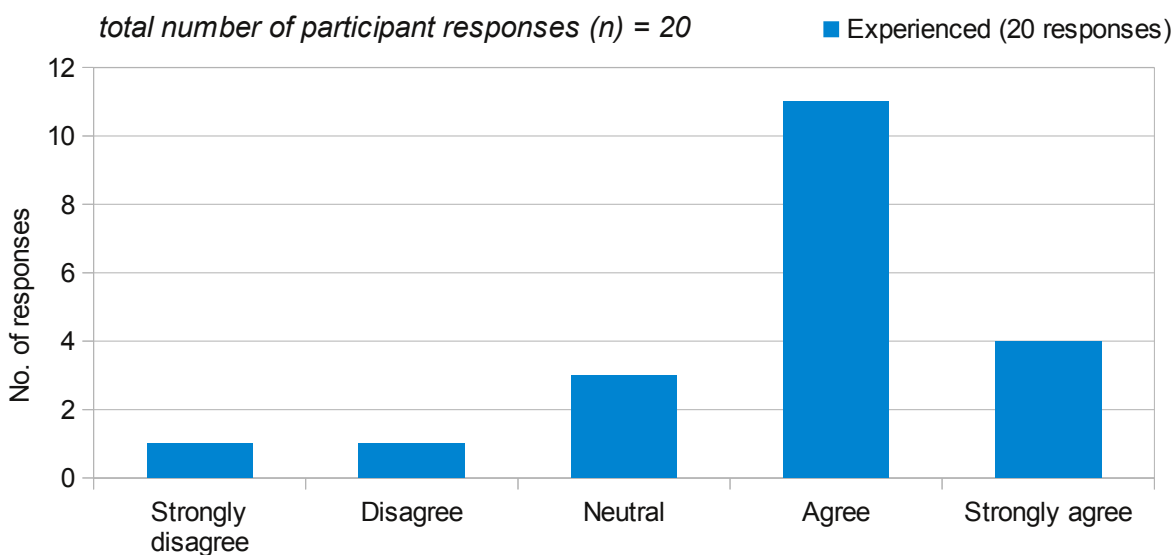
Figure 7.24. Accuracy with which FUMES represented the Challenger mining environment

The simulation accurately represented the environmental conditions at Challenger during a fire underground
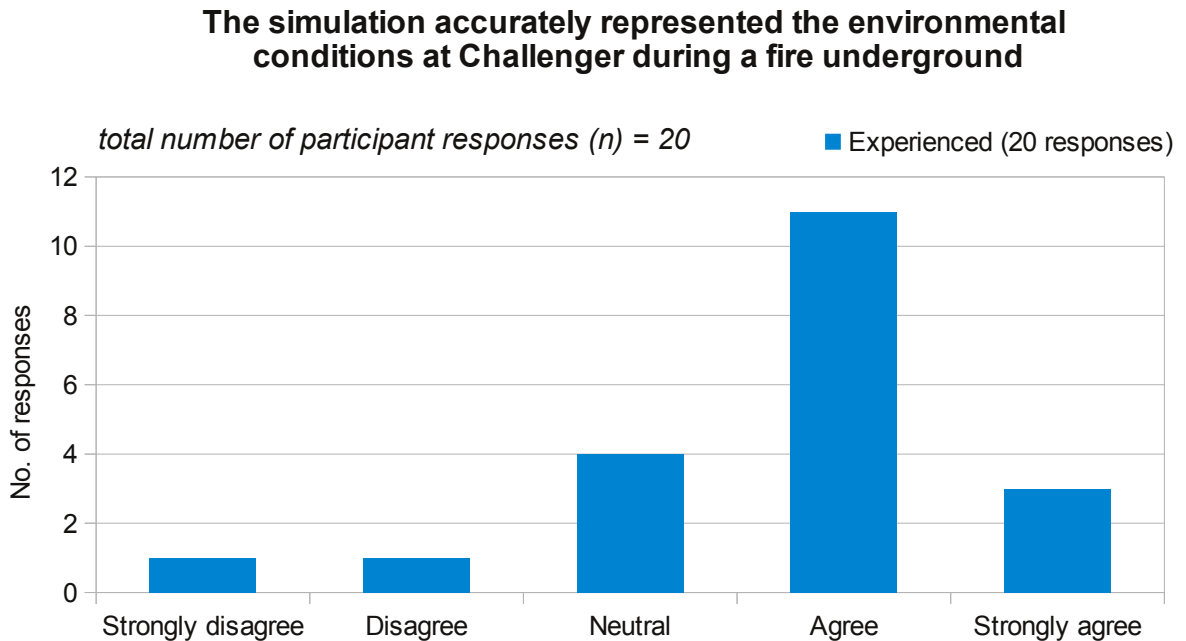
Figure 7.25. Accuracy with which the 3D simulation environment represented environmental conditions during an underground fire Challenger

Obstacles faced by Experienced Participants during problem-solving activity were consistent with those encountered during emergency evacuations of the Challenger mine (Fig. 7.23). The 3D simulation environment provided an accurate representation of the Challenger mining environment (Fig. 7.24) and faithfully depicted the environmental conditions during an underground fire (Fig. 7.25).

Interview responses were also elicited using four Experienced Participants in relation to the physical similarity of the virtual mine compared to that at Challenger. These Experienced Participants indicated that the virtual mine was physically similar to the real world mine where a direct comparison between them was possible:

- "It was sufficiently similar, it looked sufficiently similar that it was interesting and that you felt like doing it ...";
- " ... it did seem very similar";
- "As far as the level plans go, the levels that are covered at the stage that the photos and videos are taken, it's pretty good", and;

• "Yeah, it was amazing how similar it was. It was good."

Subsequent questionnaire prompts were employed assessing a variety of aspects pertaining to the physical fidelity of the simulation environment using both Experienced Participants and Novice Participants (Figs. 7.26 and 7.27).

The simulation clearly represented the Challenger mine
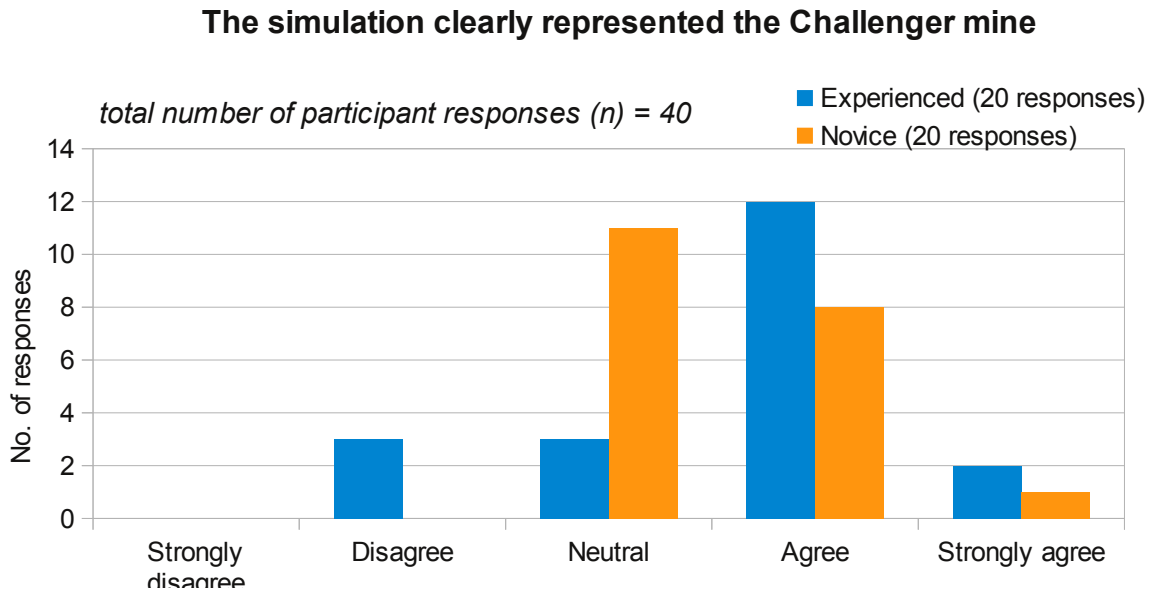
Figure 7.26. Clarity with which the 3D simulation environment represented the Challenger mine

The 3D environment looked realistic
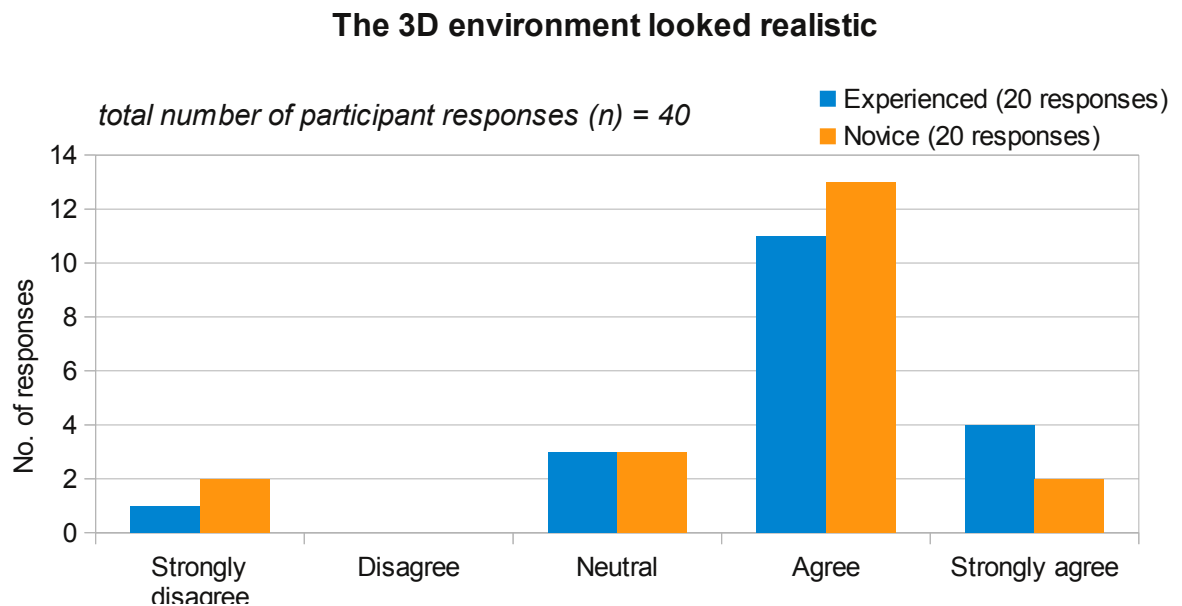
Figure 7.27. Visual realism of the 3D simulation environment

Experienced Participants viewed the simulation as a clearer representation of the Challenger mine than Novice Participants (Fig. 7.26), which may be attributed to their greater familiarity with the Challenger mining environment. However, the clear majority of both Experienced Participants and Novice Participants deemed the 3D simulation environment to be visually realistic (Fig. 7.27).

Collectively, the feedback elicited via questionnaire and interview demonstrated that the virtual mining environment was physically similar to the real world mining environment at Challenger. Experienced Participants indicated that the 3D simulation environment accurately represented the Challenger mine, including the obstacles and environmental conditions present during an underground fire emergency. Interview responses indicated that Experienced Participants were familiar with the virtual mining environment as a result of it's physical similarity to the real world mine, and as such, they viewed it as a clearer representation than Novice Participants. Both Experienced Participants and Novice Participants indicated that the 3D simulation environment was visually realistic.

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Functional Fidelity

The functional fidelity of the simulation environment, pertaining to the manner in which the representation reacts to action upon it (Towne, 1995), was evaluated using a combination of questionnaire and interview prompts using Experienced Participants and Novice Participants. The questionnaire responses assessed the manner in which movement and physical exertion functioned within the 3D simulation environment (Figs. 7.28 through 7.33).

Moving up the decline required more physical effort than moving down the decline within the simulation
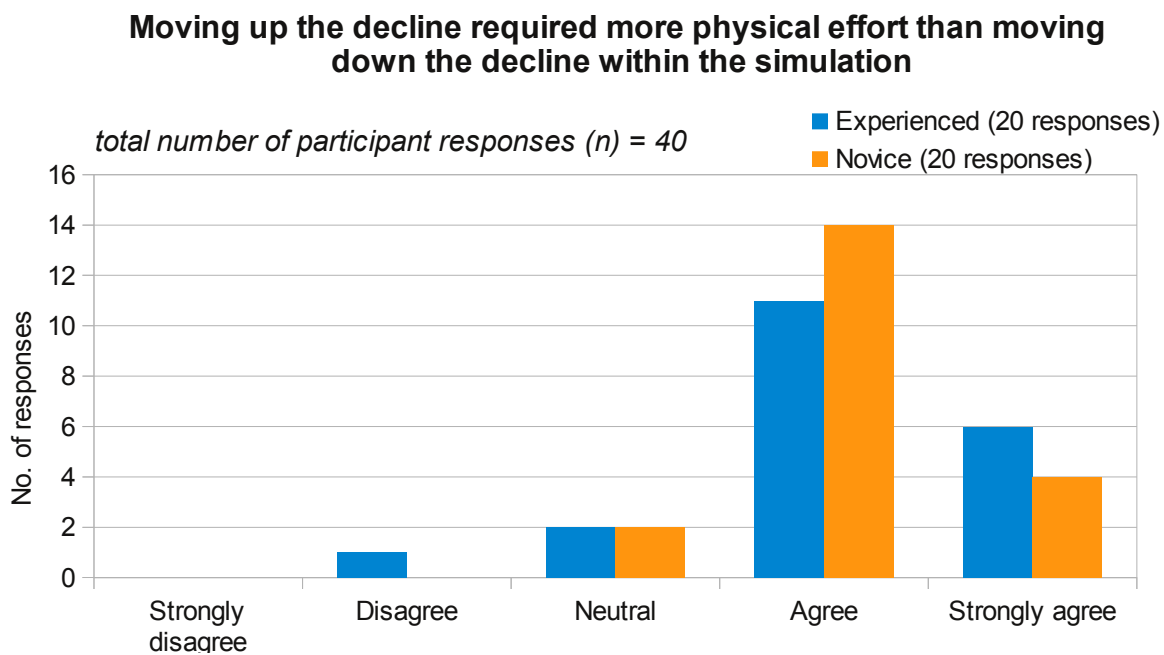
Figure 7.28. Physical effort function in relation to the inclination of the terrain

**Running required more physical
effect than walking within the simulation**

total number of participant responses (n) = 40

■ Experienced (20 responses)
■ Novice (20 responses)
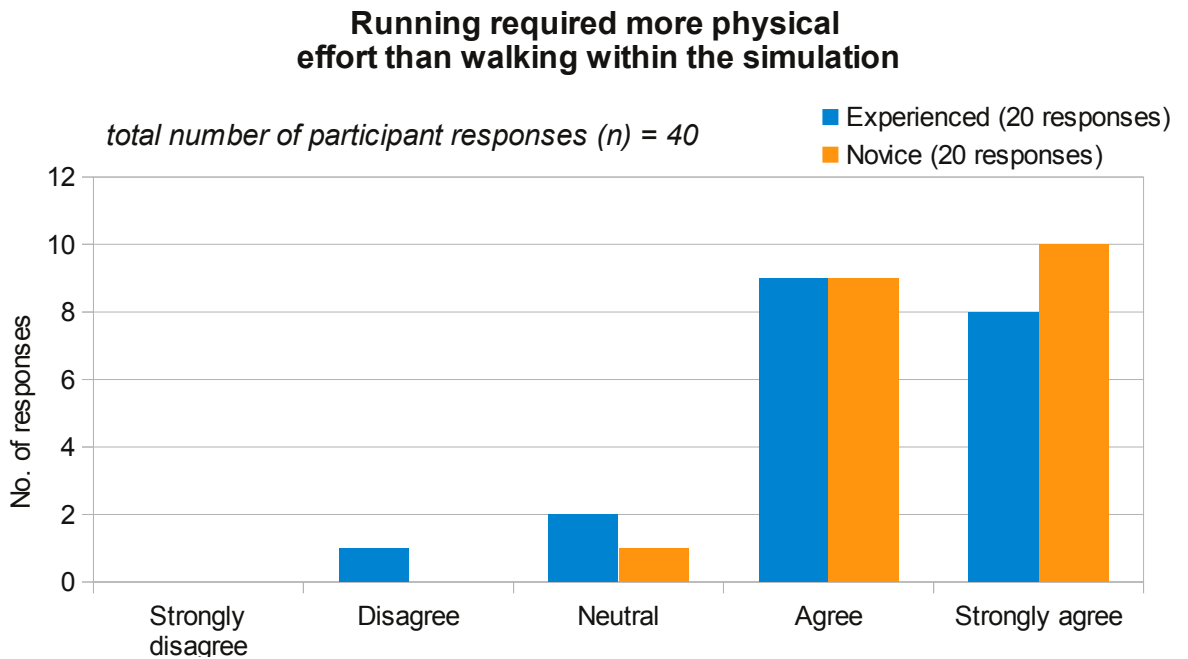
Figure 7.29. Physical effort function in relation to the speed at which the user was moving

**Climbing an escape rise required a
great deal of physical effort within the simulation**

total number of participant responses (n) = 40

■ Experienced (20 responses)
■ Novice (20 responses)
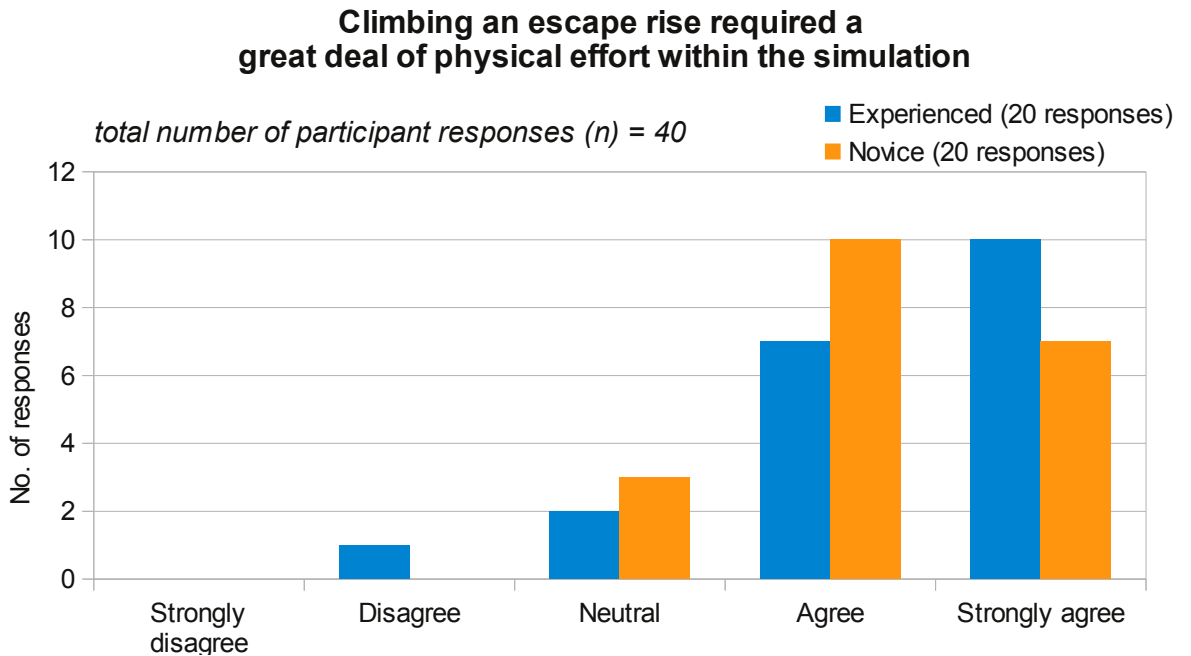
Figure 7.30. Extent to which climbing an escape rise required a great deal of physical effort

The signs attached to the walls within the 3D environment indicated which level I was on and the direction of escape rises
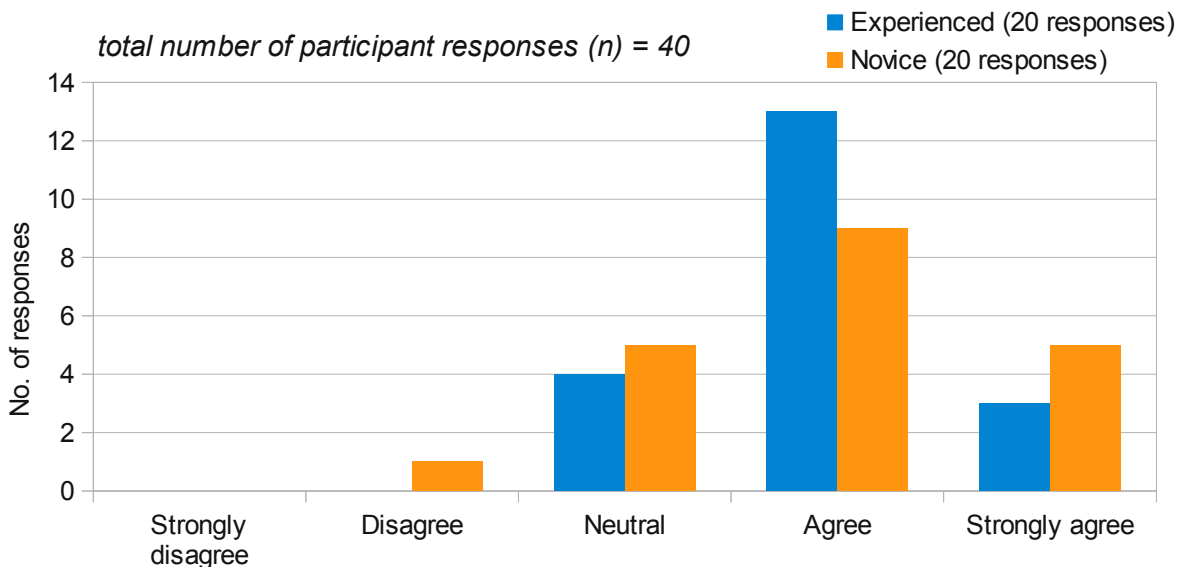
Figure 7.31. Functionality of signs as indicators of the user's location and that of escape rises

I knew when I had walked or run into objects within the 3D environment
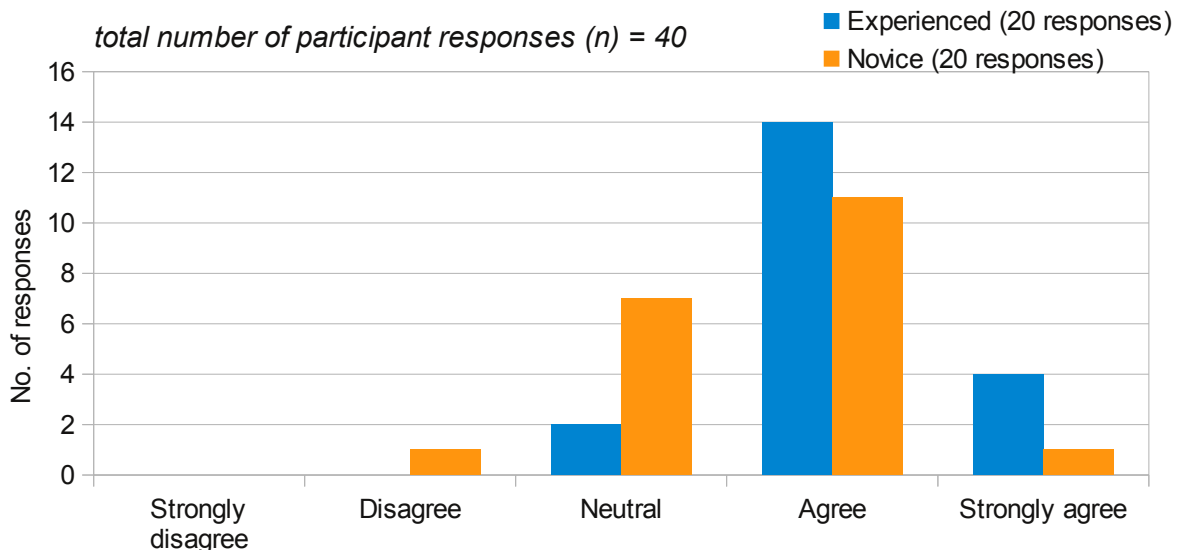
Figure 7.32. Extent to which objects appeared solid

250

I knew when my movement was obstructed by a solid object within the 3D environment
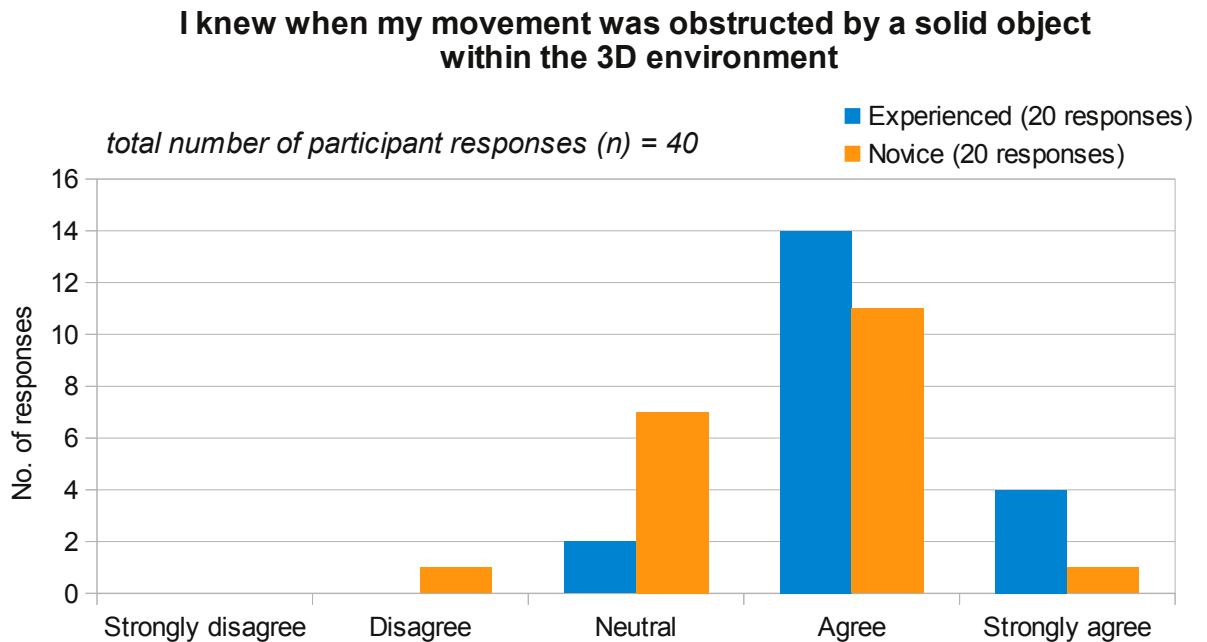
Figure 7.33. Extent to which solid objects could be identified

Physical effort corresponded to the inclination of the terrain (Fig. 7.28) as well as movement speed (Fig. 7.29). Climbing an escape rise in the virtual mine required a great deal of physical effort (Fig. 7.30), while signage functioned as effective indicators of participants' location and the location of escape rises (Fig. 7.31). Participants also identified objects within the virtual mine as being solid constructs which could impede movement when collided with (Figs. 7.32 and 7.33).

Experienced Participants were further queried via interview in relation to the functionality of the virtual mine compared to the mine at Challenger. Responses suggested that movement, terrain inclination, physical exertion, self-rescuer oxygen consumption, and signage within the virtual mine functioned in a manner that was consistent with their real world counterparts during user interaction:

- " … it was accurate the way the decline went up and down and went into the levels and you found your little escape ways, the signs were accurate for your levels and your escape way.";
- "Yeah, the movements felt right, but I just wasn't sure when you walked from one level down to another for the refuge chamber, the amount of time it actually took. But then

> when you got the little print out thing at the end, it said how long you took to walk there and you think oh well, yeah it did, but it didn't feel that long so to speak", and;

- "I think so. From what I remember, you don't have a massive amount of interaction with the environment itself. It's kind of just walking levels and climbing escape ways, so yeah, for the small amount of interaction with the environment that you do have, yeh, if you're walking uphill, the simulator tells you that you're working harder. If you're walking uphill with your self-rescuer on, you use more of it. So yeah, the small amount that you do, yeah it does reflect it. "

The questionnaire and interview responses demonstrate that self-rescuer oxygen consumption varied in accordance with physical effort, which itself was determined by the movement speed and the steepness of the terrain within the 3D simulation environment. Responses provided by Experienced Participants suggest that this functionality was consistent with real world experiences at Challenger. This indicates that the functionality of the simulation environment was consistent with user expectations during interaction.

Summary for Authenticity of the Simulation Environment

Authentic representation of the physical and functional characteristics of the real world problem scenario is necessary to facilitate the transfer of learning within a problem-based learning environment. Situation analysis identified the physical characteristics of the physical and functional aspects of the real world environment requiring authentic representation in order to facilitate the transfer of knowledge (Chapter 4.2.8). These were accommodated within FUMES using plans and images of the Challenger mine, escape rises, and refuge chambers to create authentic 3D models, whilst Subject Matter Experts at Challenger were consulted in relation to the function of movement, physical exertion, self-rescuer oxygen consumption, and the environmental conditions during an underground fire.

Findings elicited from the FUMES implementation indicate that the real world problem was represented with sufficient authenticity, both physically and functionally. The virtual mine was deemed to be an accurate representation of the real world mine during an emergency evacuation, comprising similar obstacles and environmental conditions. Experienced Participants indicated that they were familiar with the virtual mining environment as a result of their previous experience at Challenger, and identified the simulation more clearly than Novice Participants. Participants also indicated that movement, physical exertion, and oxygen consumption behaved

in a manner that was consistent with their experience with emergency evacuation scenarios in the Challenger mine, where the simulation functioned in a manner that was accordant with their expectations as they interacted within the virtual mine.

This suggests that FUMES effectively accommodated the physical and functional aspects of the Challenger mining environment so that participants were provided with an authentic representation which was familiar to them. Participants were thereby able to relate their experience within FUMES to their existing knowledge of emergency evacuations within the Challenger mining environment.

This indicates the need to identify and accommodate the physical and functional characteristics of the real world environment that establish authenticity in order to support the construction and transfer of knowledge in 3D, problem-based learning environments. Analysis of the data collected during the FUMES implementation indicates the following findings in relation to the authenticity of the simulation environment situational factor:

- The appearance and behaviour of the simulation environment needs to faithfully embody the key physical and functional characteristics of the real world environment such that it is familiar to users and consistent with their expectations during interaction. Prominent objects, obstacles, environmental conditions and physical characteristics, in addition to the behaviour of the real world environment which affects problem-solving activity, should be identified during the design process in order to facilitate authentic representation.

7.1.9 High Visual Fidelity

The rendering capabilities of 3D simulation environments developed using gaming technologies allow real world spaces to be represented realistically and with high visual fidelity. Situation analysis established the aspects of the 3D simulation that needed to be represented with high visual fidelity in order to represent the Challenger mining environment with sufficient physical fidelity and authenticity (Chapter 4.2.9). Visual entities identified in this regard include key 3D models and textures, such as the mine, refuge chambers, and escape rises, lighting and shadows, and fire and smoke effects.

The following sections detail the data analysis for high visual fidelity as a means of determining

the extent to which this Situational Analytical Factor was accommodated within FUMES. This was undertaken according to evaluation criteria established from the literature (Table 2.14) pertaining to the quality of visual elements, the richness of information content, the perceived sense of immersion, and the perceived sense of presence.

Quality of Visual Elements

A series of questionnaire prompts were employed using Experienced Participants and Novice Participants to measure the quality of visual elements in terms of the realism of the virtual mining environment and the quality of lighting therein (Figs. 7.34 through 7.37).

The 3D environment looked realistic
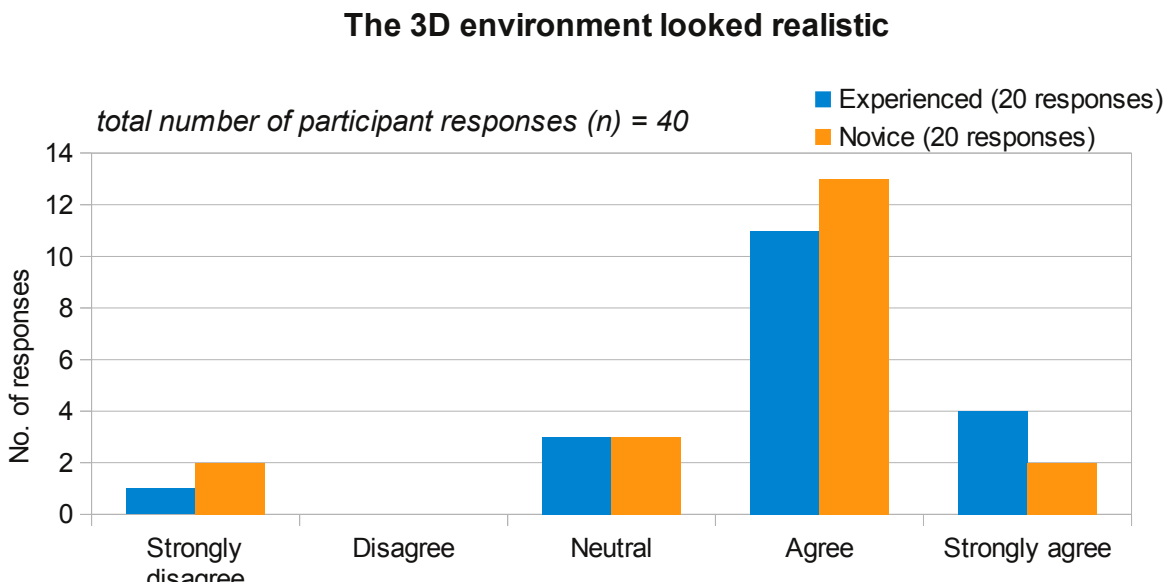
Figure 7.34. Visual realism of the 3D simulation environment

Lighting and shadows within the 3D environment were consistent with the real world mine
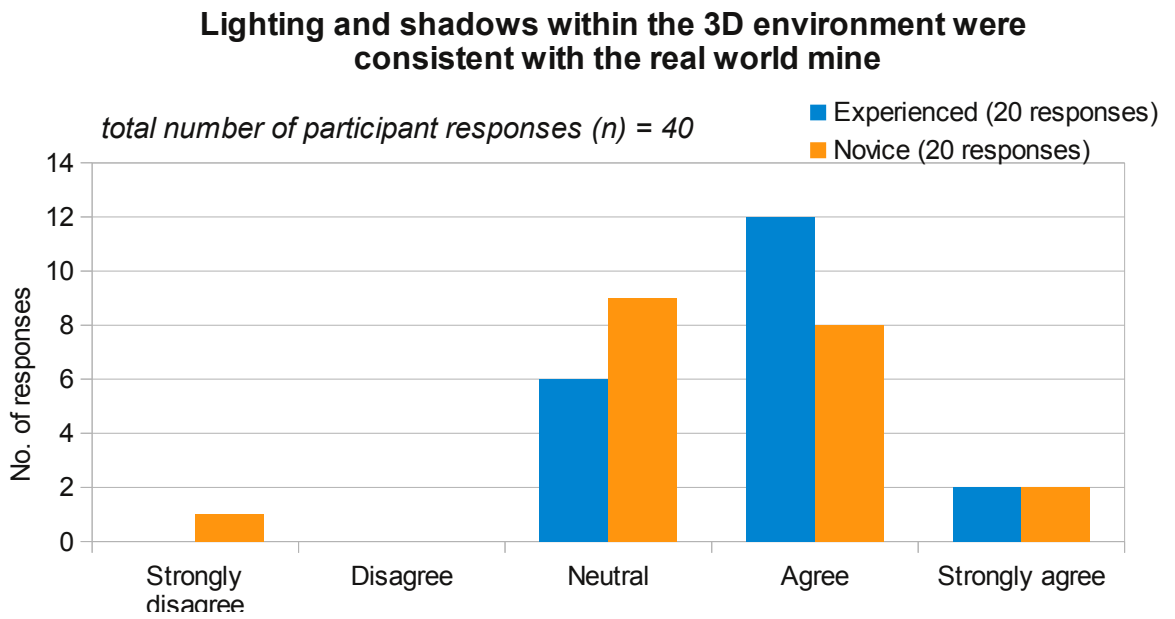
Figure 7.35. Consistency of lighting and shadows within the virtual mine compared to the real world mine

The cap lamp provided me with enough light to effectively complete the training scenarios
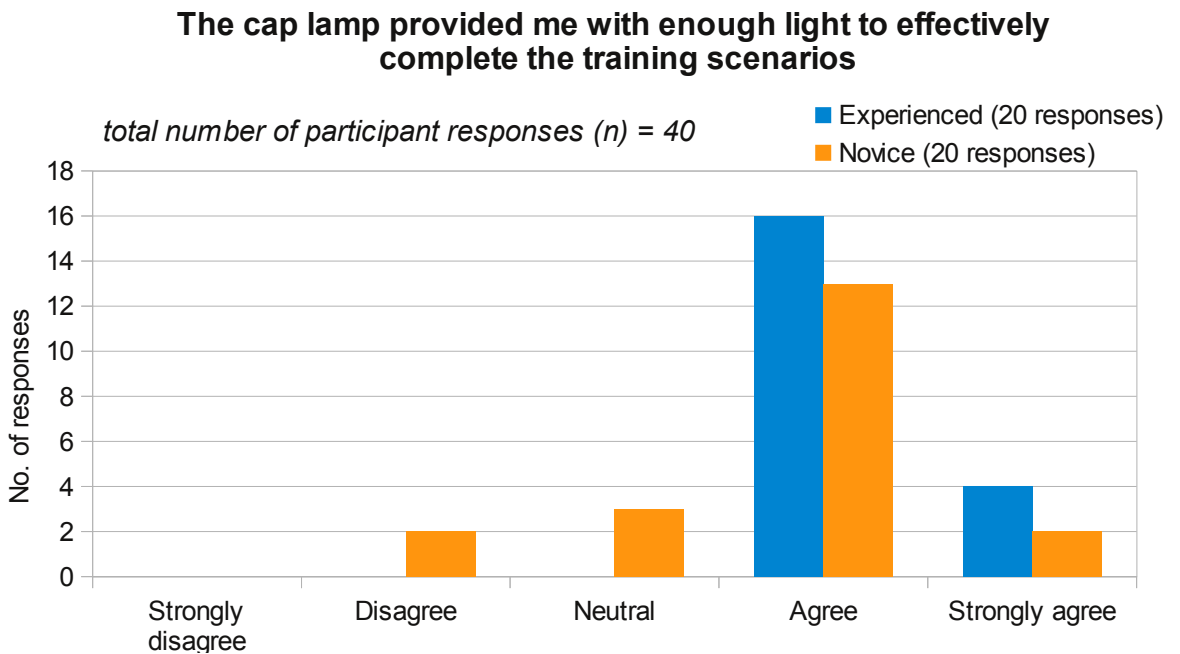
Figure 7.36. Effectiveness of lighting within the virtual mining environment

Overall, the 3D environment looked like the real world mine
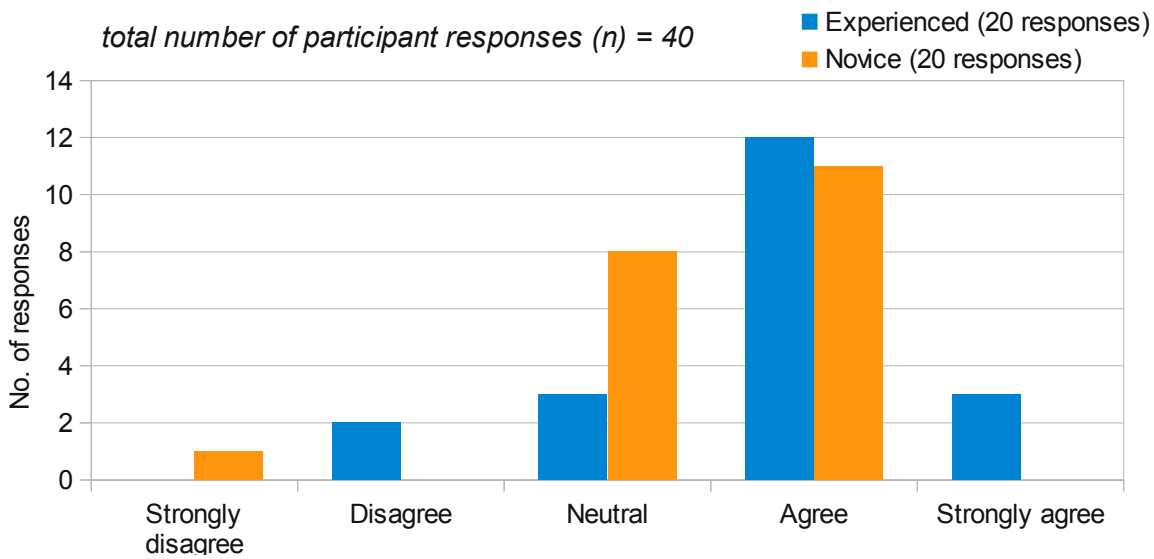
Figure 7.37. Visual similarity between virtual and real world mining environments

The virtual mining environment resembled the real world mine at Challenger and was visually realistic, although the similarity to the real world mine was more evident to Experienced Participants than Novice Participants (Figs. 7.37 and 7.34). The consistency of lighting and shadows within the virtual mine compared to the real world counterpart was more evident to Experienced Participants than Novice Participants (Fig. 7.35). A clear majority of both Experienced Participants and Novice Participants demonstrated that the cap lamp provided them with sufficient light to effectively undertake problem-solving activity within the 3D simulation environment (Fig. 7.36).

Richness of Information Content

Interview responses were elicited from four Experienced Participants and three Novice Participants to gauge the efficacy of visual information conveyed in the 3D simulation environment in addition to identifying deficiencies. Responses from both groups suggested that the visual information provided was of sufficient quality to successfully undertake problem-solving activity, but greater contextual detail would have better facilitated orientation and way-finding:

- " … you've got dark smoke, dark environments, with blacks on blacks so the screen was really difficult to follow. Some of the landmarks needed to be more prominent against all those blacks it would have been better and less frustrating";
- "I found most of the graphics to be pretty good. Some of the dead end drives, like when we started off in the level, it was just the grey end of the drive", and;
- "I think you really need to look at the specifics to what is in the mine, stuff that people of different experiences will look for. Your average green person is not going to pick up on a lot, but someone like myself and others that are in the environment a lot know to look for vent bags or firing lines, you can follow a firing line out, you can follow services out to get you out onto the decline. Once you're out on the decline you can take it from there, and I think that would probably be the big improvement"

These comments suggested that greater visual fidelity in the form of landmarks, rock wall surfaces, and servicing infrastructure such as vent bags and firing lines would have better facilitated problem resolution. This was consistent with previous analysis (Chapter 6.2), which highlighted the importance of servicing infrastructure as spatial cues within the real world mine and that their absence within the virtual mining environment subsequently affected participant performance in terms of orientation and navigation.

Perceived Sense of Immersion

Questionnaire and interview feedback provided by Experienced Participants and Novice Participants was analysed in order to ascertain the perceived sense of immersion within the virtual mining environment. Questionnaire responses were elicited in relation to the extent to which participants experienced feelings of detachment, excitement, and urgency within the 3D simulation environment (Figs. 7.38 and 7.39).

I felt detached from the real world as I was using the simulation
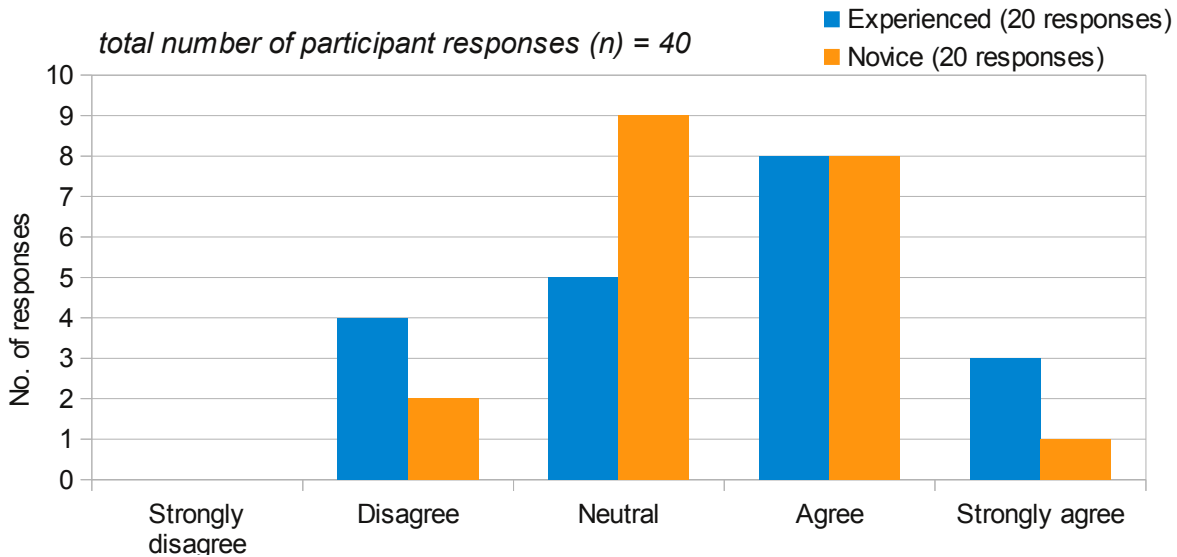
Figure 7.38. Sense of detachment whilst undertaking problem-solving activity within the 3D

simulation environment

**I felt a sense of urgency or excitement whilst
completing the training scenarios**
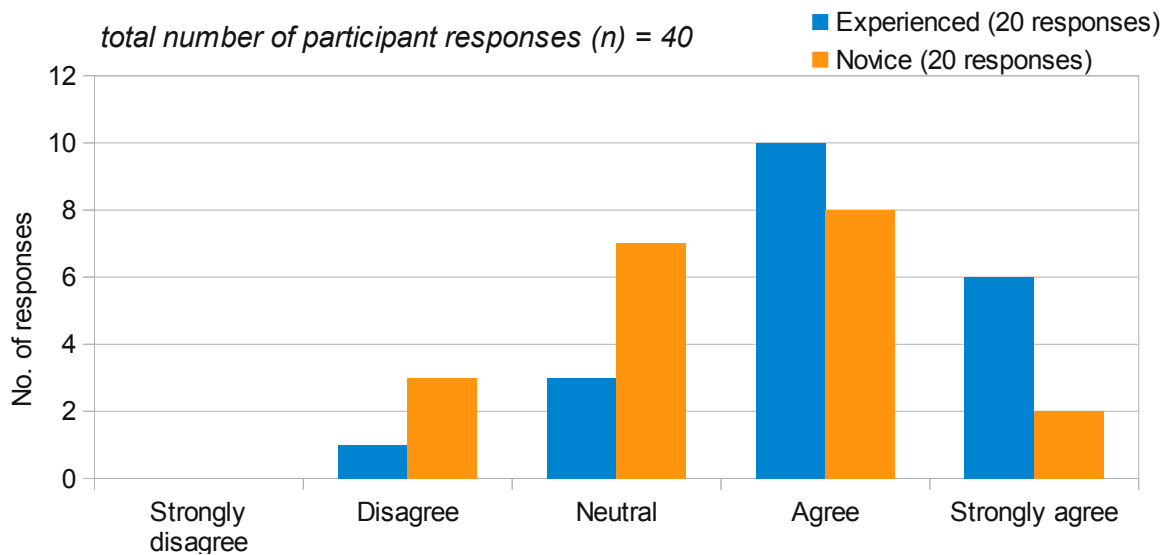
Figure 7.39. Sensations of urgency and excitement whilst undertaking problem-solving activity

within the 3D simulation environment

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Problem-solving activity within the 3D simulation environment did not consistently engender feelings of detachment from the real world amongst Experienced Participants and Novice Participants (Fig. 7.38). However, Experienced Participants and Novice Participants indicated greater coherency in relation to sensations of urgency and excitement (Fig. 7.39).

Interview feedback provided by four Experienced Participants and three Novice Participants as to whether they felt immersed in an emergency situation whilst undertaking problem-solving activity in FUMES were similarly varied:

- "Felt like I was sitting behind a computer.";
- "Not really immersed in it, I suppose it felt like a simulation.";
- "You sort of felt a bit of urgency, but you still knew that if you didn't make it, nothing would've happened."
- " I felt a bit immersed, like excited.";
- "Yeh, it did. It made you more alert, you know you're in an emergency and you've got to think and focus on that.", and;
- "Yeh, yeh, I found it surprisingly real. You're in the scenario and you're there and you have to get out, and what are you going to do?"

The questionnaire and interview responses demonstrate that the 3D simulation environment did not instil a sense of immersion amongst participants consistently. Whilst some participants exhibited feelings of detachment and urgency during problem-solving activity, others indicated that they were aware that they were operating a simulator.

Perceived Sense of Presence

Previous analysis (Chapter 7.1.7) indicated that participants did not perceive a clear or persistent sense of presence within the virtual mining environment, although feedback provided by one Experienced Participant suggested that the ability to move freely within the virtual mine contributed to a feeling of presence. Given that participants demonstrated the ability to successfully complete the problem-solving task (Chapter 6.1.1), this suggests that the lack of presence was not an impediment.

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Summary for High Visual Fidelity

The high visual fidelity inherent in gaming technologies makes it possible for 3D simulation environments that exist within a problem-based learning pedagogy to accommodate visual characteristics of real world problem scenarios in a realistic manner. Situation analysis indicated that the mining environment, refuge chambers, escape rises, lighting and shadows, and fire and smoke would need to be represented with high visual fidelity in order to represent the Challenger mining environment with sufficient physical fidelity and authenticity (Chapter 4.2.9). In order to accommodate this, a combination of high quality 3D models, textures, and particle effects were developed from images and source material provided by Subject Matter Experts at Challenger.

Findings elicited from the FUMES implementation regarding the quality of visual elements, richness of information content, perceived sense of immersion, and perceived sense of presence indicated sufficient visual fidelity within the 3D simulation environment to represent the Challenger mine. The appearance of the virtual mine and the lighting exhibited therein was deemed to be consistent with the real world counterpart by Experienced Participants, while both groups of participants indicated that the virtual mine looked realistic. However, visual deficiencies were identified in relation to a lack of contextual detail in rock wall surfaces and prominent spatial cues which negatively impacted on participants ability to orientate and navigate within the virtual mining environment. The extent to which the 3D simulation environment instilled a sense of immersion varied amongst participants, with some reporting feelings of detachment and urgency during problem-solving activity. Presence was not instilled consistently amongst participants, although this did not impede problem-solving performance.

This suggests that FUMES effectively accommodated the visual characteristics of the real world mining environment where participants were provided with a representation that was consistent with their existing knowledge and experience. The fidelity of the visuals were sufficient for completing problems-solving activity, but insufficient to instil a sense of presence or immersion amongst participants consistently. Furthermore, greater fidelity in the form of the visual cues that facilitated orientation and navigation within the real world mine, such as vent bags and servicing infrastructure, could have improved participant performance within the 3D simulation environment. While high visual fidelity was designated as necessary for visual cues within the virtual mine, a number of omissions and compromises were made with respect to the representation of vent bags and servicing infrastructure within the virtual mine due to limits in

the time available for the development of FUMES during the study (Chapter 5.2.4).

This indicates the need to identify and accommodate aspects of the real world problem that need to be represented with high visual fidelity in order to support the construction and transfer of knowledge in 3D, problem-based learning environments. Analysis of the data collected during the FUMES implementation indicates the following findings in relation to the high visual fidelity situational factor:

- Objects within the real world environment related to the resolution of the problem need to be represented with high visual fidelity within the simulation environment in order to facilitate the effective transfer of knowledge. In practice, this means that one should identify and represent these objects with sufficient visual quality and detail so that they can be recognised and utilised by users in accordance with their existing knowledge of the real world environment. A problem-solving task which required users to administer the correct treatment for a patient with a broken leg would need objects such as the femur, tibia, and fibula bones to embody the necessary visual detail such that users could correctly identify the trauma and determine the appropriate treatment, for example, and;

- Instilling sensations of presence and immersion consistently requires a level of visual fidelity that may exceed that which is required to effectively undertake problem-solving activity. In designing, one should identify whether the emotional factors surrounding the real world problem, such as immersion and presence, are important to the learning objectives, and subsequently determine whether the additional visual fidelity is warranted within the 3D simulation environment.

7.2 Situational Design Considerations

Situational design considerations differ from Situational Analytical Factors in that the designer can exercise control over the way in which they are characterised within the 3D simulation environment. These factors are incorporated into the design of the simulation environment to accommodate the corresponding overlapping Situational Analytical Factors which have been previously established (Chapter 2.5). The role of Situational Design Considerations during the FUMES implementation and their validity as design considerations will be explored in the following sections:

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- Chapters 7.2.1 through 7.2.3 examines the structuredness, complexity, and domain specificity of the problem-solving task;
- Chapters 7.2.4 and 7.2.5 scrutinises problem representation and the authenticity of information in the problem-solving task, and;
- Chapter 7.2.6 evaluates user control afforded within the 3D simulation environment.

7.2.1 Structuredness

Structuredness denotes the perceived certainty or familiarity of a problem as determined in accordance with a problem-solver's existing problem-solving knowledge and experience. The structuredness of the problem-solving task in FUMES situated problem-solving activity within the context of emergency evacuations at Challenger in order to appeal to participants' existing real world knowledge (Chapter 4.3.1). The problem-solving task was structured so that users were informed that an underground fire emergency had occurred within the Challenger mining environment and that they needed to evacuate to a refuge chamber. They were also provided with some initial information to identify their location, the location of smoke, and the location of the nearest refuge chamber within the virtual mine. However, users were not provided with instructions regarding how to safely reach a refuge chamber. Thus, the problem-solving task was designed with a well-structured goal state, partially ill-structured initial state, and ill-structured solution method.

The following sections detail the data analysis for structuredness as a means of determining the efficacy of this Situational Design Consideration within FUMES. This was undertaken according to evaluation criteria established from the literature (Table 2.15) pertaining to the extent of existing domain specific knowledge and general problem-solving skills, as well as the perceived familiarity of the problem.

Extent of Existing Domain Specific Knowledge and General Problem-solving Skills

A series of questionnaire prompts were employed in order to ascertain the existing domain specific knowledge and general problem-solving skills that Experienced Participants and Novice Participants had prior to using the simulation (Figs. 7.40 through 7.49).

Before using the simulation, I knew the procedure for an emergency evacuation at Challenger
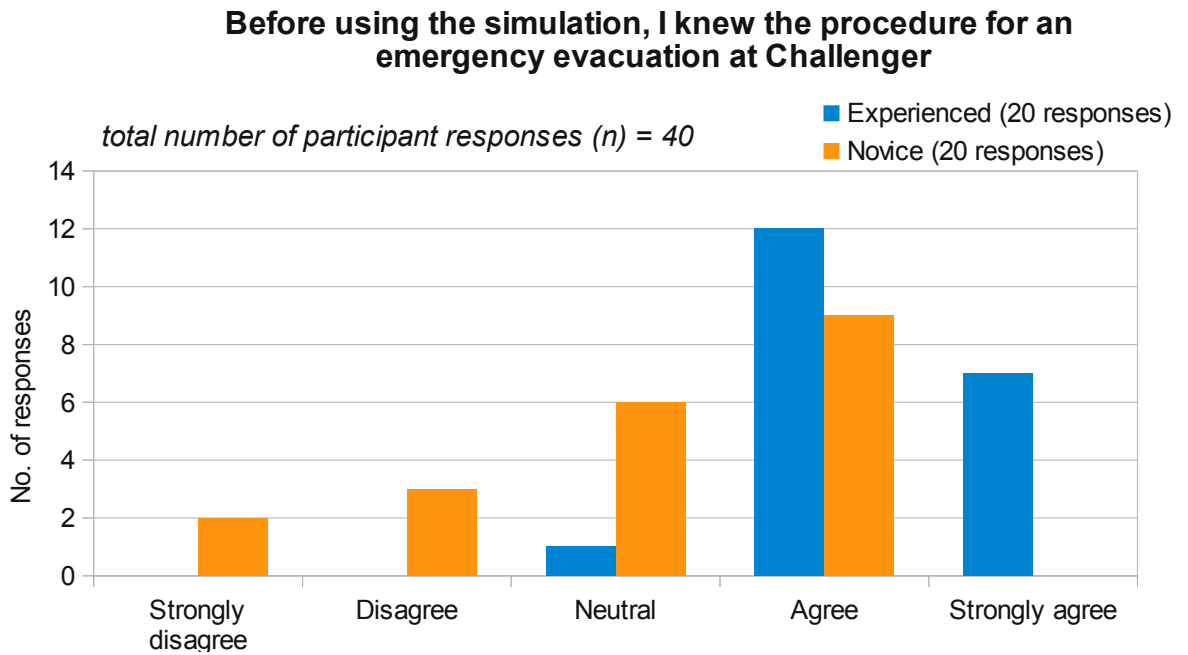
Figure 7.40. Knowledge of the emergency evacuation procedure used at Challenger prior to using FUMES

Before using the simulation, I knew the layout and structure of the Challenger mine and could confidently travel from one location to another
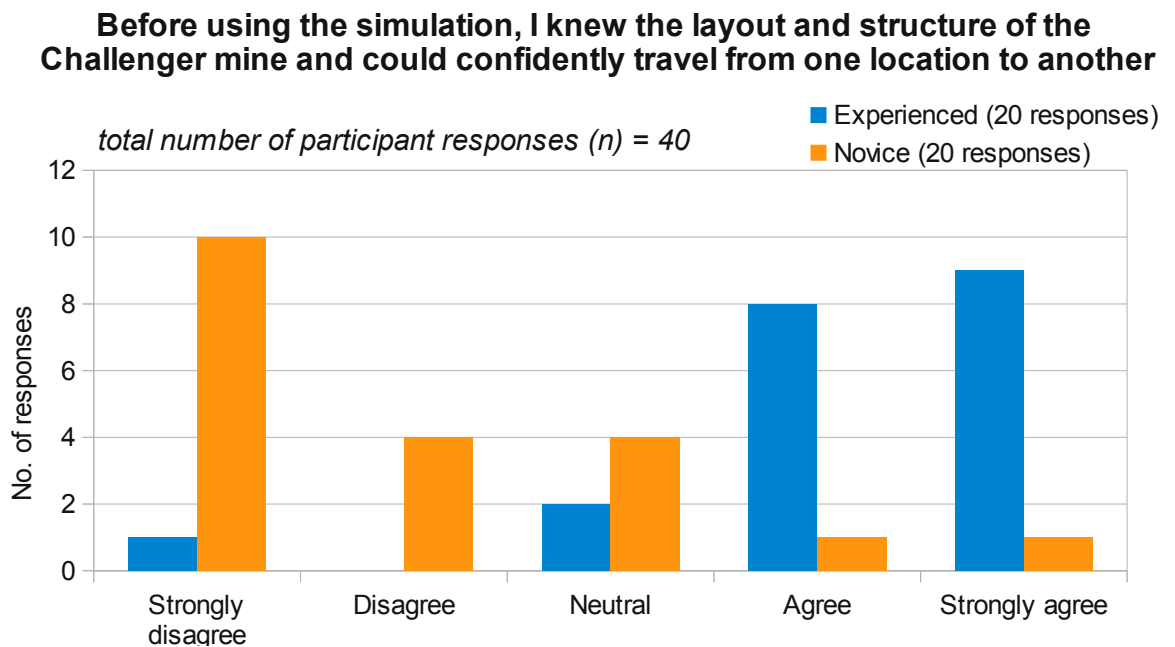
Figure 7.41. Knowledge of the Challenger mine relating to layout, structure, and navigation prior to using FUMES

Before using the simulation, I knew where the refuge chambers and escape rises were located in the Challenger mine

total number of participant responses (n) = 40

■ Experienced (20 responses)
■ Novice (20 responses)
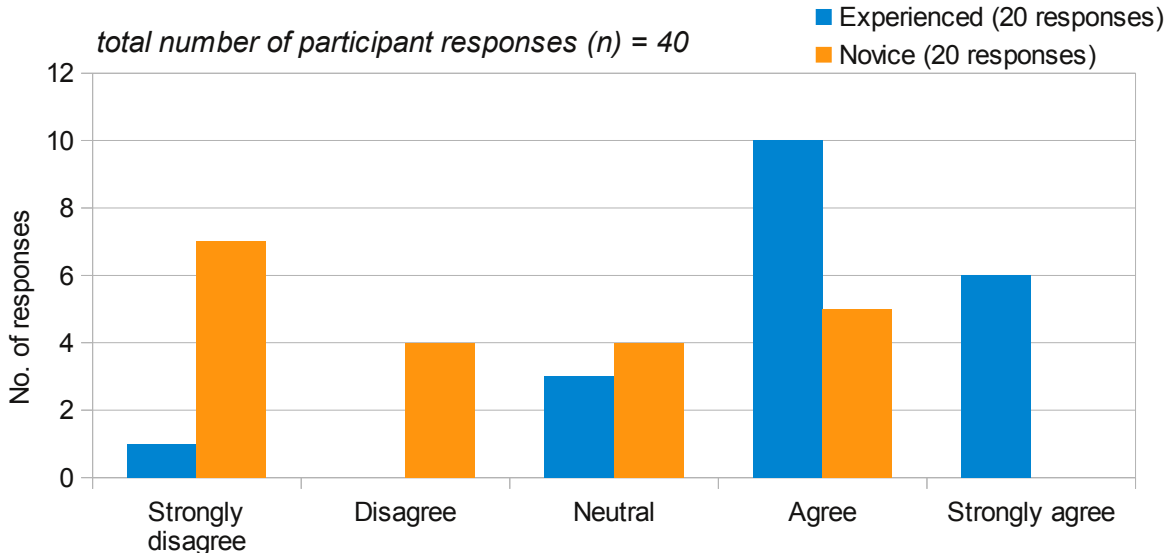
Figure 7.42. Knowledge of the locations of refuge chambers and escape rises at Challenger prior to using FUMES

Before using the simulation, I knew the correct procedure for using my self-rescuer during an emergency evacuation

total number of participant responses (n) = 40

■ Experienced (20 responses)
■ Novice (20 responses)
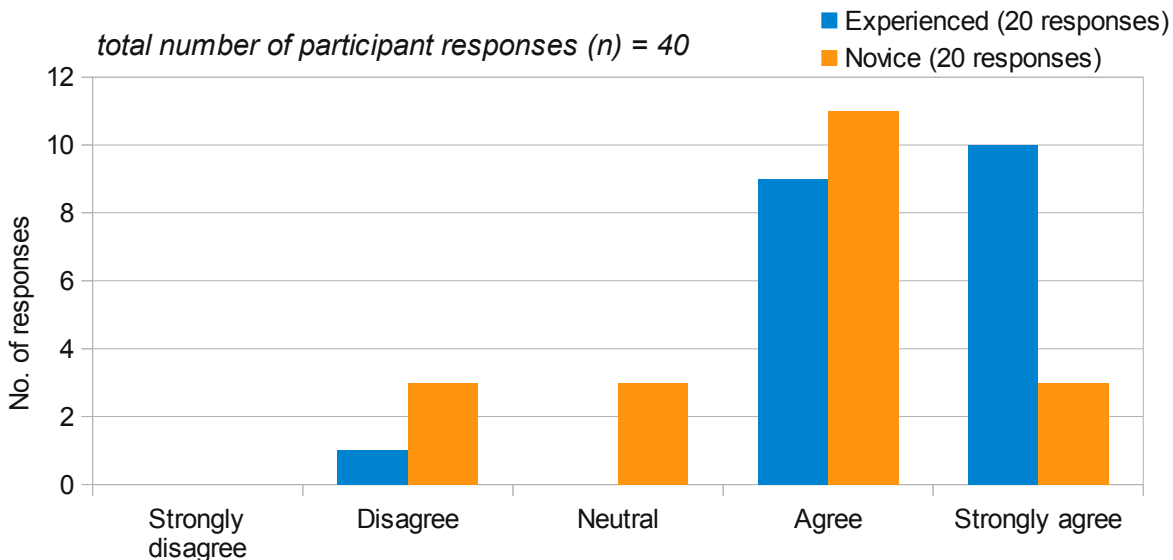
Figure 7.43. Knowledge of the locations of refuge chambers and escape rises at Challenger prior to using FUMES

Before using the simulation, I knew how long the oxygen in a self-rescuer would last for
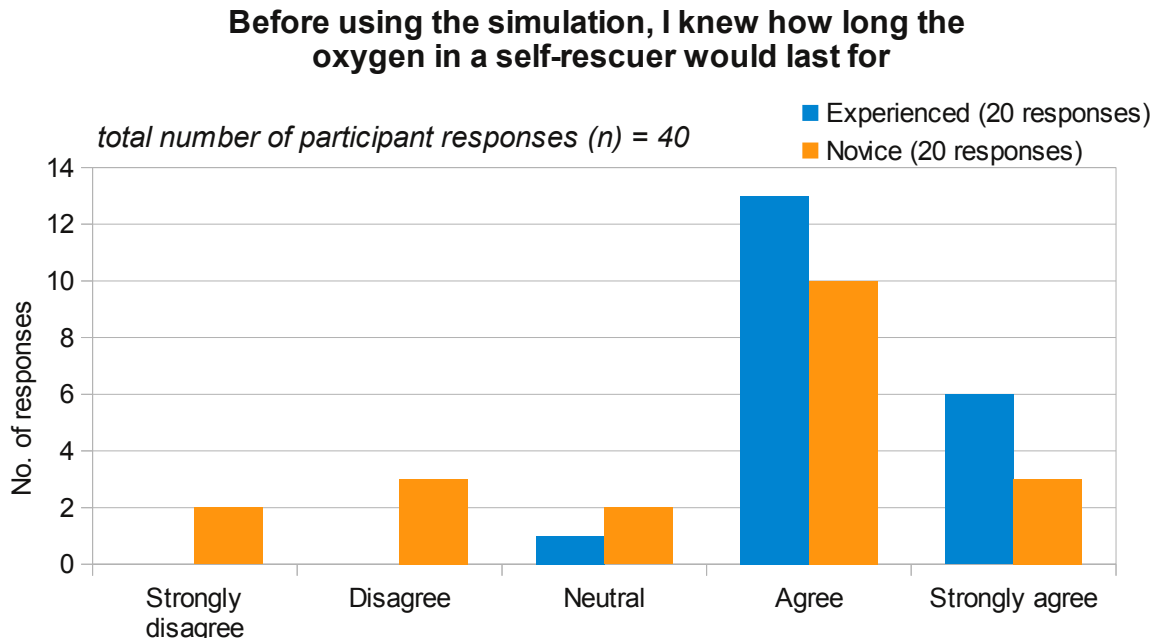
Figure 7.44. Knowledge of self-rescuer duration prior to using FUMES

Before using the simulation, I knew how to make the oxygen supply in a self-rescuer last as long as possible
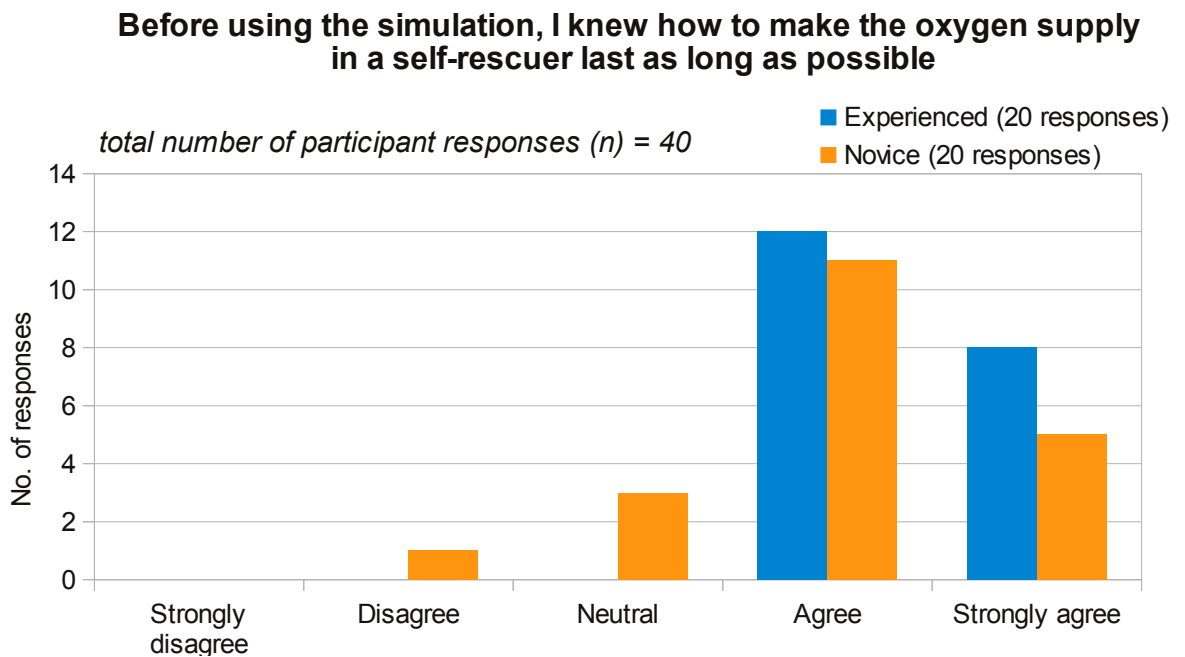
Figure 7.45. Knowledge of self-rescuer application prior to using FUMES

Before using the simulation, I knew when to use an escape rise during an emergency evacuation
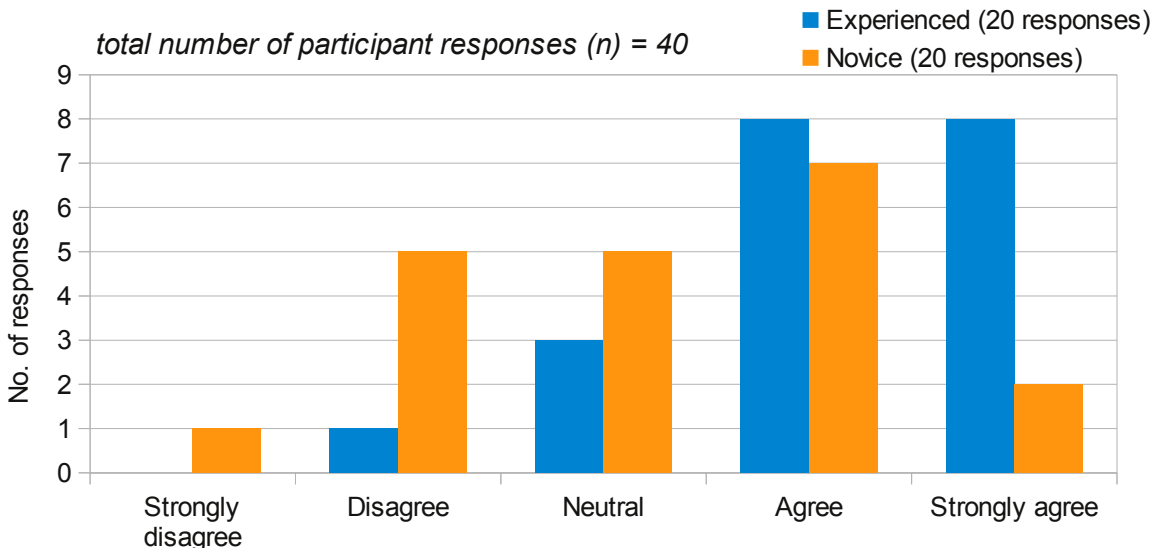
Figure 7.46. Knowledge of escape rise usage prior to using FUMES

Before using the simulation, I knew what stench gas was used for at Challenger
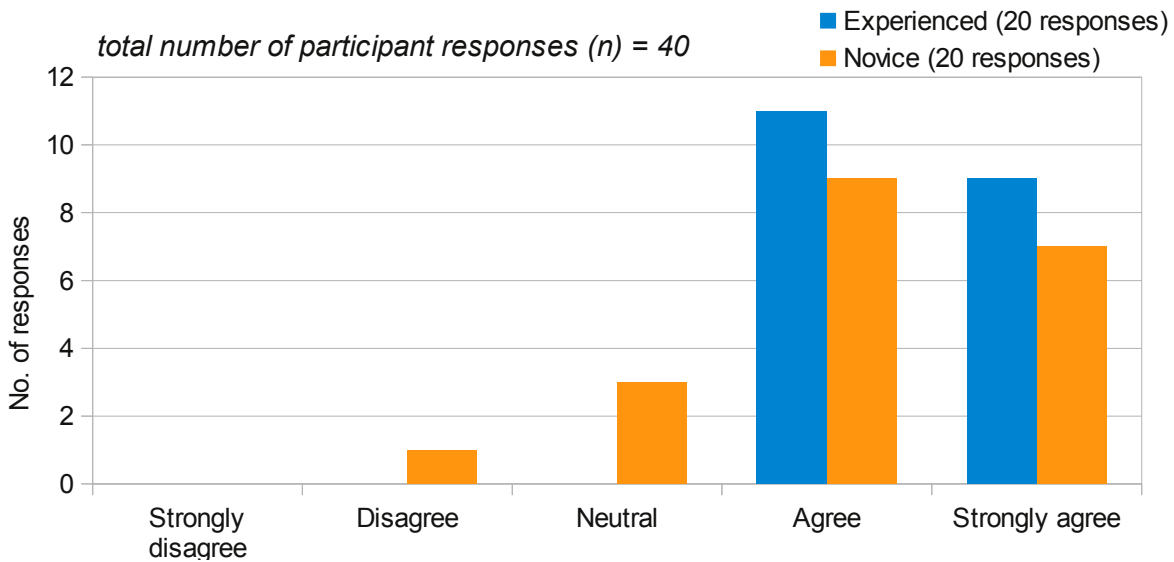
Figure 7.47. Knowledge of stench gas prior to using FUMES

I am good at solving problems
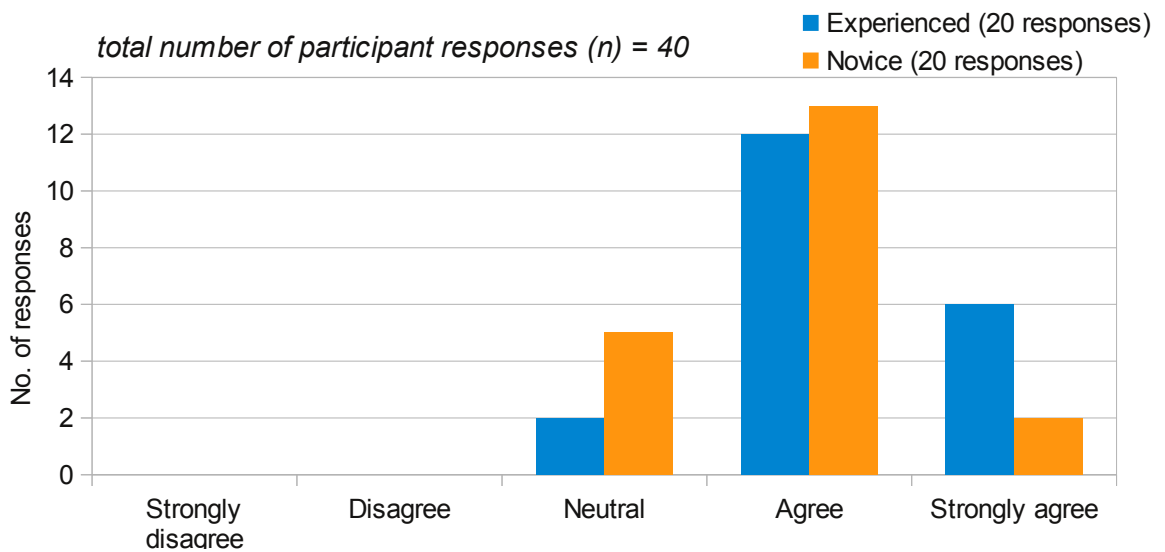
Figure 7.48. Perceived problem-solving ability prior to using FUMES

I can solve problems that I'm not familiar with
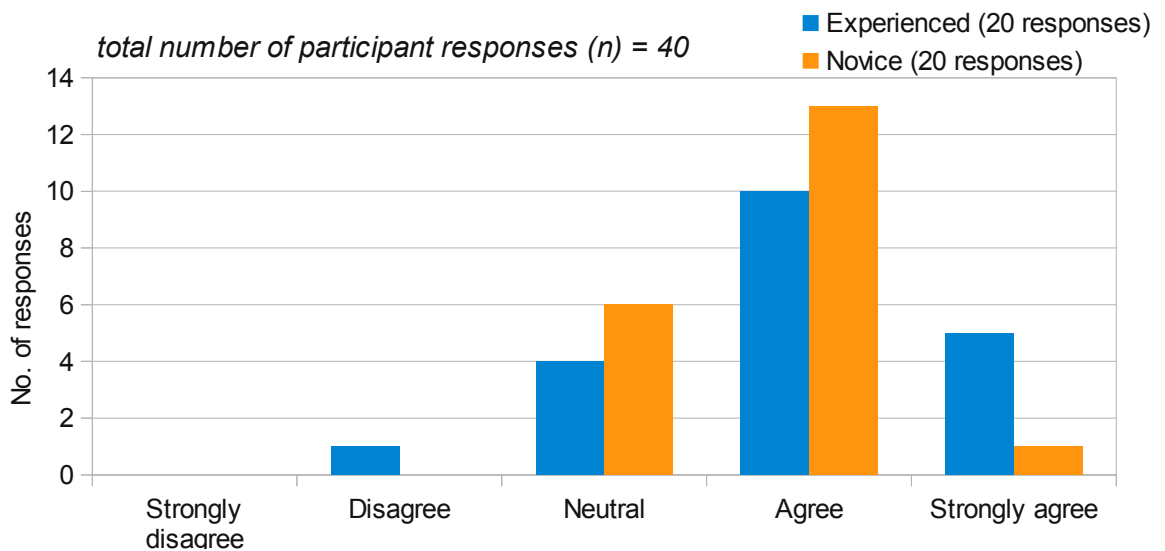
Figure 7.49. Perceived ability to solve unfamiliar problems prior to using FUMES

Prior to using the simulator, Experienced Participants possessed greater knowledge of the emergency evacuation procedures used at Challenger than Novice Participants (Fig 7.40). Experienced Participants also had a far better understanding of the layout and structure of the mine, including the locations of escape rises and refuge chambers. They were more confident in

navigating between locations (Figs. 7.41 and 7.42), and were much more knowledgeable regarding the use of escape rises during an emergency evacuation (Fig. 7.46). In contrast, existing knowledge relating to self-rescuer usage (Figs. AP through AR) and the significance of stench gas (Fig. 7.47) was comparative between Experienced Participants and Novice Participants. Both groups of participants highly regarded their problem-solving skills and ability to resolve unfamiliar problems (Figs. 7.48 and 7.49). Collectively, these responses suggest that the problem-solving task would have appeared more well-structured to Experienced Participants as they were more familiar with the evacuation procedure and the means by which to determine an effective route to refuge within the mining environment.

Interview prompts were employed using four Experienced Participants to provide further insight in relation to their existing knowledge of the Challenger mine and emergency evacuation procedures prior to using FUMES. Responses suggest that Experienced Participants had a well developed understanding of the Challenger mine and the emergency evacuation procedures used therein before they used the simulator:

- "I've done a few mock emergencies here, we've done the stench gas and going to refuge chambers and all that sort of stuff, so you've got a good understanding of it all."
- "We've had to do our trainings, when we do our inductions, we have to do a bit of safety training, but I haven't been in an emergency situation where I've had to put it into practice. One time, when I got dusted out I was able to … evacuate in a vehicle and go somewhere above the dust out. Air was being sucked down the decline, so I just went and sat above the level that was being dusted, so the vent wasn't blowing my way. ", and;
- "When I was looking for refuge chambers, I generally speaking knew which way to go. I was finding the refuge chambers where I expected them to be where I was looking for them. If I hadn't been underground before then I think it would have been much more difficult to do. "

The questionnaire and interview responses thus provided a very clear indication of the relative disparity in knowledge and experience with emergency evacuations at Challenger between Experienced Participants and Novice Participants. The greatest disparity was evidenced in relation to knowledge of, and ability to navigate within, the Challenger mining environment. This was consistent with previous analysis demonstrating that Experienced Participants were more effective at orientating and navigating within the virtual mine compared to Novice

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Participants (Chapters 7.1 and 7.2). Given that the solution method to the problem-solving task was ill-structured, this indicated that Novice Participants were more likely to encounter difficulties during problem resolution than Experienced Participants.

Perceived Familiarity of the Problem

Experienced Participants and Novice Participants were queried as to the familiarity and clearness of the problem-solving task within FUMES (Figs. 7.50 through 7.52).

The training scenarios seemed familiar to me
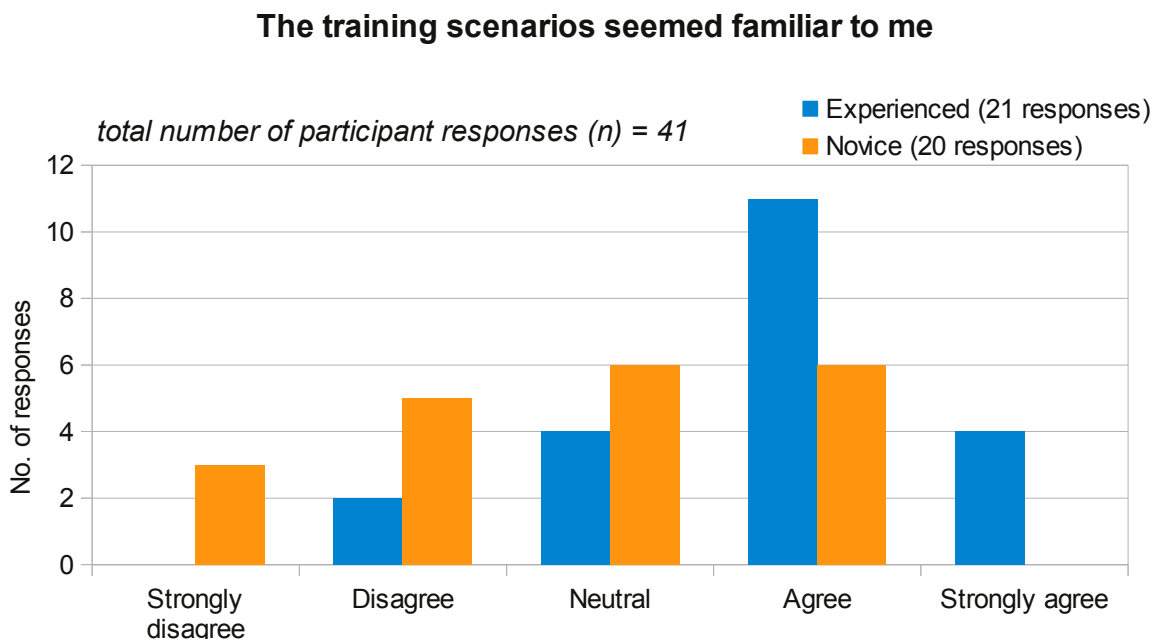
Figure 7.50. Familiarity with the problem-solving task

**I knew what to do and where to go at the beginning
of each training scenario**
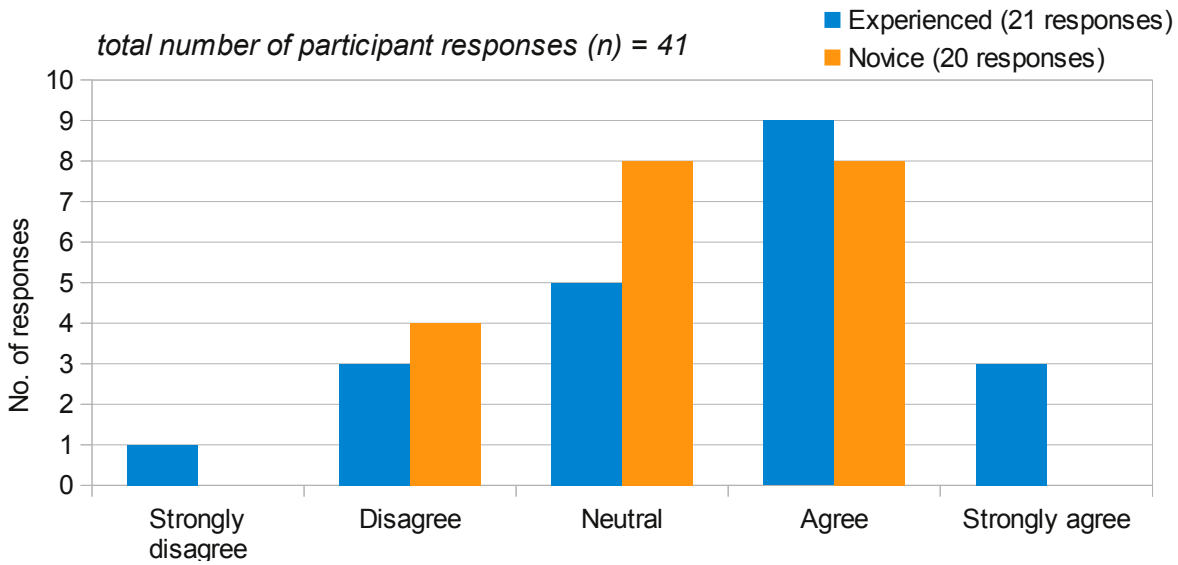
Figure 7.51. Clarity of the initial state of the problem-solving task

**The way to complete each training scenario
was clear to me**
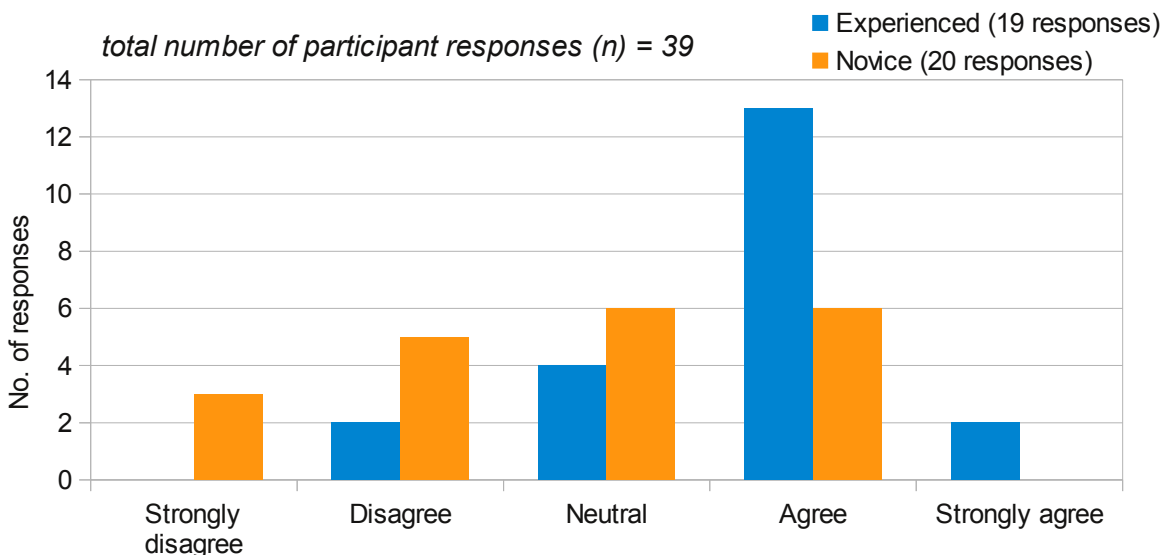
Figure 7.52. Clearness of the solution method for the problem-solving task

Experienced Participants were more familiar with the problem-solving task (Fig. 7.50) and were

more clear about the required solution method (Fig 7.52) than Novice Participants. The initial state of the problem-solving task was also perceived with greater clarity by Experienced Participants (Fig. 7.51), although the variation in responses indicated that some Experienced Participants were not sure what to do or where to go at the onset of problem-solving activity.

Four Experienced Participants and three Novice Participants were further queried during interview in relation to the aspects of the problem-solving task that seemed clear or familiar to them. The Experienced Participants indicated familiarity with the status lights and locations of refuge chambers in addition to stench gas dispersion as a method for initiating an emergency evacuation. Comments also suggested that the procedure required to evacuate the virtual mining environment was familiar based on knowledge of emergency evacuation procedures at Challenger:

- "... the plan of attack that I had in my head seemed to fit in with the scenarios";
- "I seemed to be able to try and do that in the simulation, so it was doing what I expected to be able to do", and;
- "When you're in that sort of environment all the time, it just needed things like that to jog your memory, it doesn't take much at all, sort of like autopilot in a way."

Conversely, the interview feedback elicited from Novice Participants did not detail familiar aspects of the problem-solving task to the same extent as that of Experienced Participants. One Novice Participant identified the terrain, vehicles, refuge chambers, and escape ladders as being familiar to them. In contrast, another indicated that the problem-solving task confused them due to a lack of experience within the Challenger mining environment.

Further interview responses were elicited as to participants' perception of the problem-solving task in relation to their existing knowledge of emergency evacuations at Challenger. Statements made by Experienced Participants indicated that the problem-solving task was consistent with a real world emergency evacuation at Challenger, and as such, allowed knowledge of the emergency evacuation procedure to be used to aid resolution:

- "I thought it was very good, I think it would be good for everyone to do it, because you don't want to have to be in a real life emergency situation to be able to practice it and know what to do";
- "That's definitely how things happen and it's pretty appropriate to this sort of

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environment", and;

· "It called upon me personally to use everything I was aware of."

In contrast, the responses from Novice Participants did not denote the same level of familiarity with the problem-solving task. Statements made by two of the Novice Participants indicated that the problem-solving task within FUMES provided a suitable representation of emergency evacuations at Challenger, which suggested some degree of familiarity. However, these responses provided little in the way of descriptive detail.

Given the relative disparity in existing knowledge and experience between Experienced Participants and Novice Participants, a further interview question was utilised to compare perceptions of the problem-solving task. Whilst the sparse responses provided by Novice Participants suggested that they had difficulty relating their existing knowledge and experience to problem-solving activity in FUMES, those provided by Experienced Participants indicated that they perceived the problem-solving task with familiarity and certainty:

· "That's definitely how things happen and it's pretty appropriate to this sort of environment.;

· " It called upon me personally to use everything I was aware of.", and;

· " … the plan of attack I had in my head seemed to fit in with the scenarios."

Collectively, the questionnaire and interview responses demonstrate that Experienced Participants were better acquainted with the problem-solving task than Novice Participants as a result of greater familiarity with emergency evacuations at Challenger. Experienced Participants indicated that the problem-solving task was well situated with respect to the real world problem, and demonstrated greater awareness of the solution method. As such, Experienced Participants employed approaches to resolution which were consistent with those that they would use during a real world emergency evacuation at Challenger. In contrast, the questionnaire and interview responses provided by Novice Participants did not suggest a great deal of familiarity with the problem-solving task in FUMES. This indicated that the problem-solving task was largely unfamiliar to Novice Participants and that it may have been too ill-structured given their limited knowledge of the real world problem domain.

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Summary for Structuredness

Structuredness delineates the extent of uncertainty that learners encounter during problem-solving activity in relation to their existing knowledge of the problem domain. The structuredness of the problem-solving task in FUMES was designed to reflect the information that would be available during the real world problem, whereby participants were informed that they needed to seek refuge in response to an underground fire in a simulated representation of the Challenger mining environment (Chapter 4.3.1).

Findings elicited from the FUMES implementation regarding the extent of existing domain specific knowledge and general problem-solving skills, the perceived familiarity of the problem, and the classification of the problem indicated that participants identified the structure of the problem-solving task in accordance with their existing knowledge of emergency evacuation procedures at Challenger. Consistent with previous analysis (Chapters 7.1, 7.2, and 7.3), Experienced Participants demonstrated that their existing knowledge and understanding of emergency evacuations at Challenger was more extensive than that of Novice Participants. This disparity was particularly evident in relation to knowledge of the spatial characteristics of the Challenger mine, and knowledge that facilitated navigation within this environment, which corresponded with Experienced Participants' superiority at orientating and navigating within the virtual mine (Chapters 7.1 and 7.2). Experienced Participants were thus more familiar with the problem-solving task, which they deemed well situated with respect to the real world problem. Furthermore, Experienced Participants had greater awareness of the solution method, whereby they employed approaches to resolution which were consistent with those that they would use during a real world emergency evacuation at Challenger.

This implies that the structure of the problem-solving task called upon participants' existing knowledge of the problem domain in order to resolve a problem that was well situated in relation to emergency evacuations of the Challenger mine. The structure of the problem required the application of existing contextually relevant knowledge in order to bridge the gap between the information which established the initial state and goal state, and the method required for solution. The disparity in existing contextually relevant knowledge between Experienced Participants and Novice Participants was thus a determinant factor in relation to how clear and familiar the the problem-solving task appeared to be. As such, the problem-solving task would have been more ill-structured for Novice Participants, particularly in relation to the solution method which required them to orientate and navigate within the virtual mining environment in

order to reach a refuge chamber. Given that Novice Participants required assistance from the Training Staff Member to reach refuge (Chapter 7.1.1), this indicated that the solution method was too ill-structured, or that more information needed to be provided during the problem statement in relation to navigation methods within the mining environment.

This indicates the need for the structuredness of the problem-solving task to afford the existing contextually relevant problem-solving knowledge of the user in addition to embodying the situatedness of the real world problem. Analysis of the data collected during the FUMES implementation indicates the following findings in relation to the structuredness Situational Design Consideration:

- The structuredness of the problem-solving task needs to situate the problem within a context that is familiar to users in order to elicit existing knowledge. This means that the problem statement needs to identify the context of the problem-solving task in terms of the environment that it is situated in and the nature of activity that is to occur, and;
- The structuredness of the problem-solving task needs to reflect the information that is available during the real world problem in order for it to appear well situated. The information provided by the problem statement specifying the initial state, goal state, and solution method must therefore be designed to be consistent with the information which would be available at the onset of the real world problem. However, users must be able to solve the problem in order to facilitate the development of knowledge, and as such, problem structure must prioritise users' existing knowledge of the problem domain in this regard. In practice, this means that additional information may need to be provided during the problem statement to address any shortcomings in the knowledge that would be needed to resolve the real world problem.

7.2.2 Complexity

Complexity denotes the extent to which elements within a problem are interrelated amongst each other and the manner in which these relationships are represented and subsequently perceived by problem-solvers. The complexity of the problem-solving task in FUMES was designed to reflect that of the real world problem in terms of the relationships between user actions and outcomes, whereby contact with fire or exposure to smoke without a functioning self-rescuer would result in failure, while safe passage through the mine to a refuge chamber

would result in successful evacuation (Chapter 4.3.2). Users were given a choice of two refuge chambers to evacuate to, given that at any point within the Challenger mine, personnel would have at most one refuge chamber above them, and one below them to chose from in the event of an evacuation. Furthermore, the complexity of the problem-solving task also encompassed relationships between movement speed, terrain inclination, physical exertion and oxygen consumption in order to elicit participants' existing knowledge of the real world problem domain within the simulation environment.

The following sections detail the data analysis for complexity as a means of determining the efficacy of this Situational Design Consideration within FUMES. This was undertaken according to evaluation criteria established from the literature (Table 2.15) pertaining to the perceived uncertainty of the problem-solving context, perception of related entities within the problem domain, and recognition of problem complexity.

Perceived Uncertainty of the Problem-solving Context

A series of three questionnaire prompts were utilised using Experienced Participants and Novice Participants in relation to the perceived state of ambiguity and uncertainty of the context in which the problem was situated (Figs. 7.53 and 7.54).
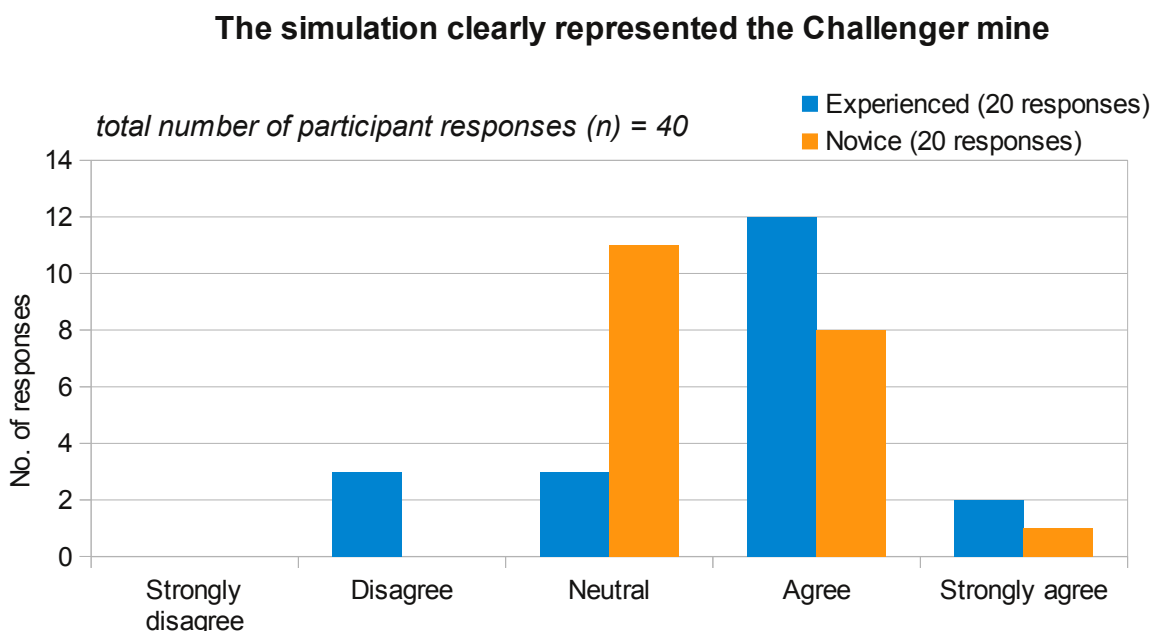
Figure 7.53. Clarity with which FUMES represented the Challenger mine

The training scenarios clearly represented an emergency evacuation of the Challenger mine
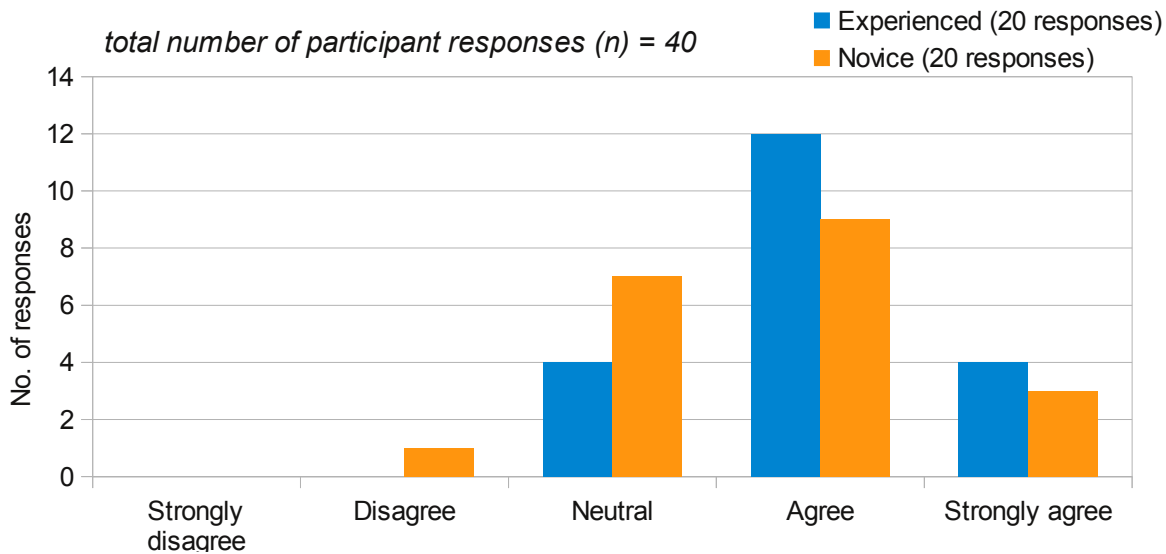
Figure 7.54. Clarity with which FUMES represented an emergency evacuation of the Challenger mine

While both Experienced Participants and Novice Participants indicated that the problem-solving task provided a clear representation of an emergency evacuation of the Challenger mine (Fig. 7.54), Experienced Participants indicated that FUMES provided a clearer representation of the Challenger mine than Novice Participants (Fig. 7.53).

Interview responses were utilised using four Experienced Participants and one Novice Participant in relation to the speed with which they were able to recognise the context of problem-solving activity. Two interview questions were used to determine how quickly they recognised the virtual mining environment as a representation of the Challenger mine, and how quickly they realised that they were in an emergency evacuation scenario. Feedback provided by Experienced Participants suggested that the presence of familiar objects and physical characteristics enabled them to quickly recognise the virtual mining environment as a representation of the Challenger mine:

- "Only a few seconds, once I started moving up the decline I noticed that I was at the seven something level";
- "Oh, virtually straight away. I think I actually started in a drive somewhere and was

straight away looking around to move out of the drive and into the decline", and;

- "Well, when it first started it seemed like the layouts and everything else, but just the level accesses onto the decline is pretty easily recognisable."

However, the participant with the least amount of experience at Challenger amongst the Experienced Participants who were interviewed indicated that they did not immediately recognise the virtual mining environment:

"I probably didn't at first, it wasn't till afterwards when I was talking to Mal (the Training Staff Member) that he said, these are our levels, and I was like, you're right, they are. It does now, now I draw the comparison. But when he first told me, I was like, ah yeah that's cool, and then yeah, I just didn't know the mine well enough."

This was consistent with the interview feedback provided by the Novice Participant which indicated that it took them twenty to thirty seconds to identify the virtual mining environment as a representation of the Challenger mine. This indicated that objects and physical characteristics within the virtual mining environment did not resonate as effectively with participants who lacked experience within the Challenger mine.

Feedback pertaining to the second interview question indicated that both Experienced Participants and Novice Participants were quick to recognise that they were situated within an emergency evacuation scenario within FUMES, with comments to this effect including "fairly quick", "pretty much straight away", and "straight away."

Thus, the questionnaire and interview feedback indicated that Experienced Participants were more certain of the environmental context of problem-solving activity than Novice Participants by virtue of their ability to quickly recognise familiar objects and physical characteristics within the virtual mine. The speed with which the environmental context could be recognised was contingent on the extent of experience participants had within the Challenger mining environment. However, participants from both groups readily recognised that problem-solving activity was established within the operational context of an emergency evacuation scenario. This suggested that the problem-solving task was more complex for Novice Participants as they were less certain of the environmental context in which problem-solving activity was situated.

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Perception of Related Entities Within the Problem Domain

Interview responses were elicited from four Experienced Participants and three Novice Participants in relation to how clearly the relationships between movement speed, physical effort, and oxygen consumption were represented within the simulation environment:

- "... running, that was having a severe affect on oxygen...";
- "... when I tried to speed up and move faster, you could hear your breathing increase and therefore got the impression that you were exerting yourself more.";
- "If you were climbing a ladder it took a bit longer. If you were walking up the decline or walking down the decline you could tell the difference.";
- "... you could tell the difference that you were breathing different. You had to take it a bit easier if you had your self-rescuer on so you didn't use it all.";
- "You put the self-rescuer on and you could hear you breathing ...", and;
- "Going uphill, breathing harder, using more oxygen compared to downhill. That was all tied in, that was good."

Consistent with previous analysis (Chapters 7.1.3 and 7.1.8), these comments indicate that the nature of the interrelationships between movement speed, terrain inclination, physical effort, and oxygen consumption within the simulation environment were clearly recognised by both Experienced Participants and Novice Participants. Furthermore, the interview responses also emphasise awareness of these relationships in relation to actions they were undertaking within the simulation environment, suggesting that the experiential nature of problem-solving activity contributed to their understanding in this regard.

Recognition of Problem Complexity

Experienced Participants and Novice Participants provided responses to a series of three questionnaires which examined their ability to recognise the complexity of the problem-solving task in terms of the choice of refuge chambers for evacuation, the number of possible outcomes, and the extent to which participants' actions influenced the outcome (Figs. 7.55 through 7.57).

I had a choice of refuge chambers to evacuate to within the simulation
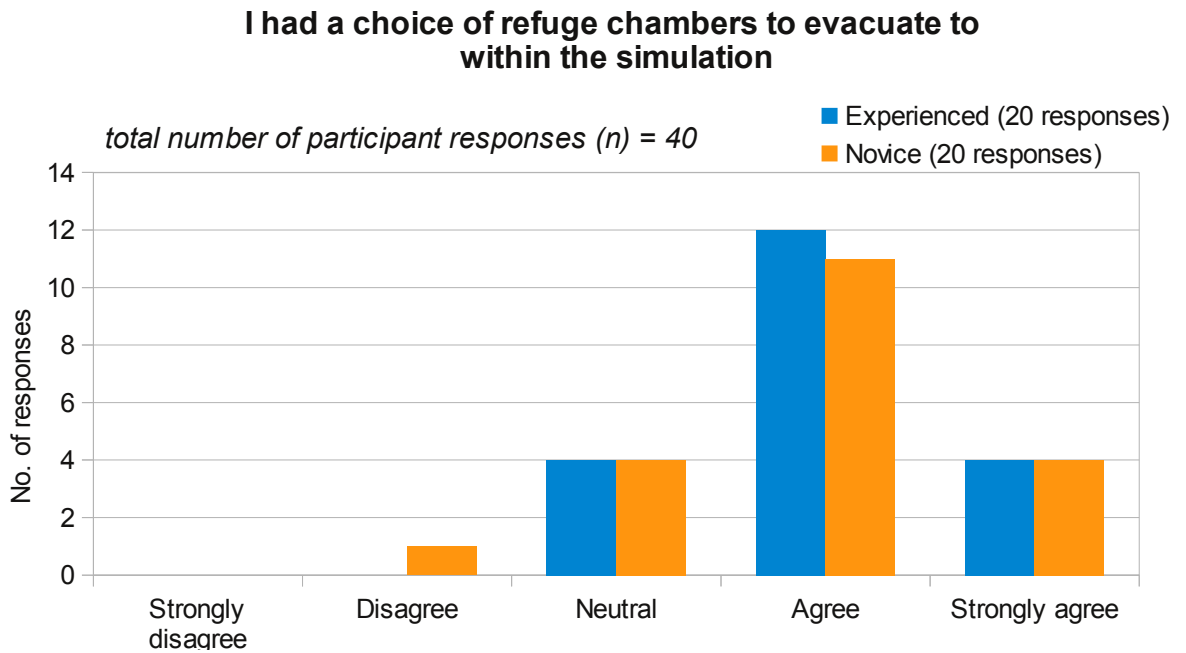
Figure 7.55. Awareness of multiple refuge chambers as points of evacuation for the problem-solving task

Each training scenario had more than one possible outcome
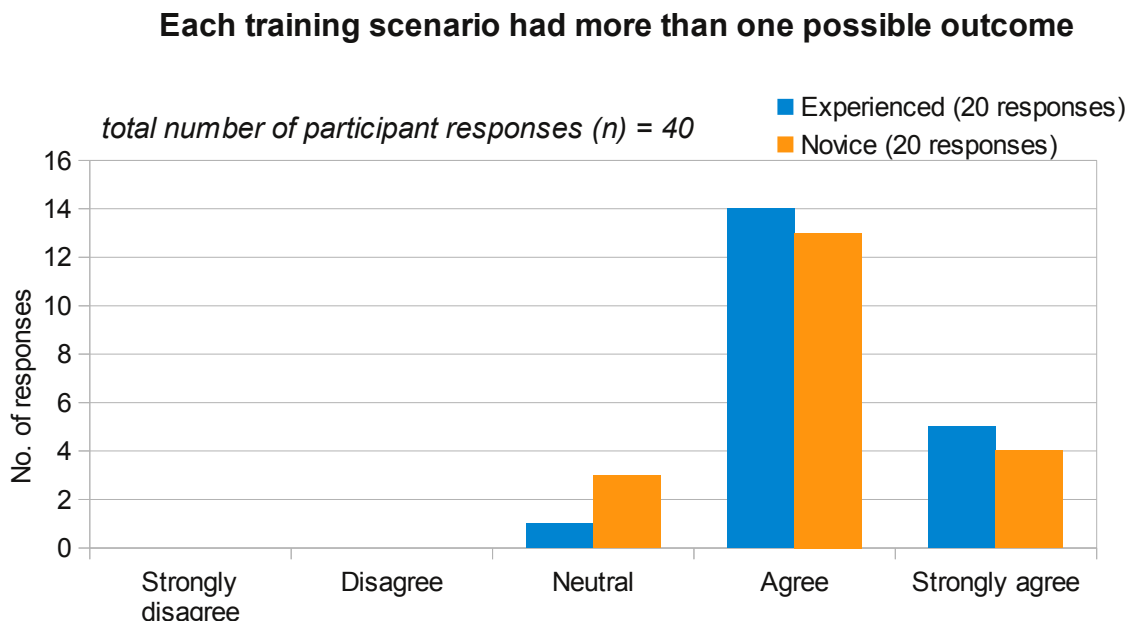
Figure 7.56. Possibility of multiple outcomes to the problem-solving task

My actions determined the outcome of each training scenario
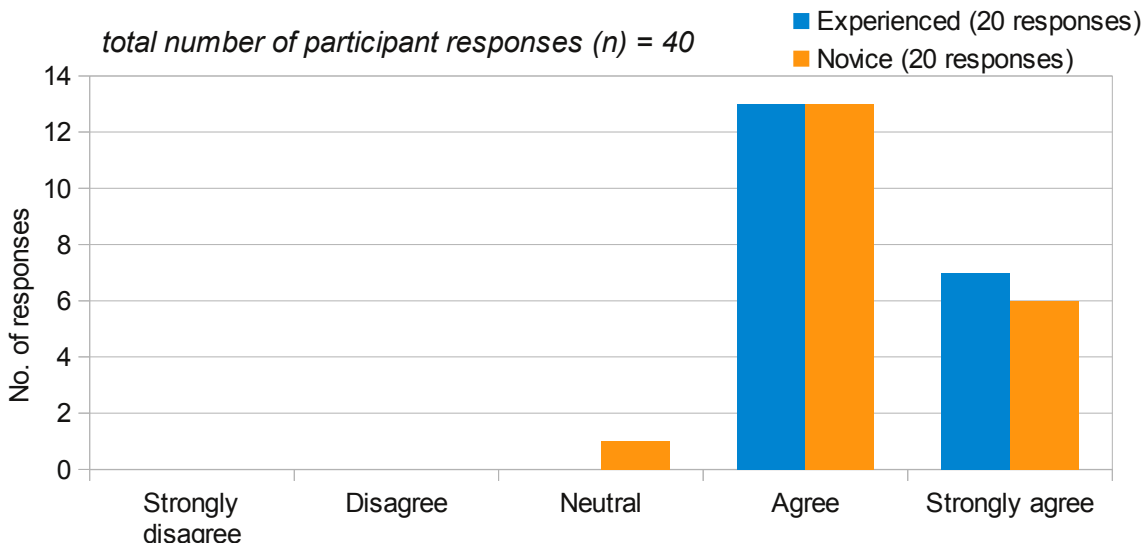
Figure 7.57. Extent to which the user's actions determined the outcome of problem-solving activity

Experienced Participants and Novice Participants indicated that the problem-solving task required them to choose a refuge chamber to evacuate to (Fig. 7.55). Participant responses to the questionnaire further inferred that the problem-solving task had more than one possible outcome (Fig. 7.56), and that their actions determined the outcome which occurred (Fig. 7.57).

Interview responses were also elicited from four Experienced Participants and three Novice Participants concerning determination of the ideal route to a refuge chamber within the virtual mining environment. Feedback provided by participants demonstrated this to be a complex operation requiring them to evaluate potential paths to refuge and effects that environmental conditions could have on the outcome, and in doing so, develop an appropriate strategy for resolution. These responses also indicate that the complexity of the problem-solving task in FUMES reflected that of the real world problem such that participants were able to utilise their existing knowledge of emergency evacuation procedures in the Challenger mine:

- "The thing for me would be to move downhill to the nearest refuge chamber and not move into danger if I knew where it was and I could avoid it. So if I had to, for instance, get to a refuge chamber and I couldn't move along the drive I would then move for an escape way and bypass the obstruction.";

- "My tendency was to use the decline unless I was near or knew where not only where the ladder was but where it led to. If it led upward to no where then I didn't use that. Mainly the decline though.";
- "Escape ways, especially if you don't know where the fire was. If you knew where the fire was, if it was above you or below you, yeh, the escape ways.", and;
- "I'd have to say the main decline, really. Escape ways, because of how our mine is set up here, I know the ventilations flows have changed now, but a lot of them can hold smoke in them, and they don't have a great deal of air flow through some of them. Although you may have smoke on the decline, the air is moving a lot quicker as well though. And I know climbing the escape ways with rescuers and climbing down them, things can get caught, and you can get caught up with bits and pieces and you can find yourself in trouble. So I'd say the primary egress is the best one. "

The questionnaire and interview responses collectively indicated that Experienced Participants and Novice Participants recognised the factors that governed the complexity of the problem-solving task in terms of the number of refuge chambers available for evacuation, the number of possible outcomes, and the affect that their actions had on determining which one of these outcomes would occur. This was reflected in interview responses detailing the process by which participants determined their route to a refuge chamber, whereby they considered the layout of the mine in relation to the routes that were available while contemplating the impact of environmental conditions within the virtual mine. This suggested that the complexity of the problem-solving task reflected that of the real world problem to the point where participants were able to utilise their knowledge of emergency evacuation procedures at Challenger towards resolution. In this manner, participants awareness and understanding of the complexity of the problem-solving task promoted the formation of strategies for achieving resolution.

Summary for Complexity

The recognition of the relationships characterised by problem complexity is contingent on the representation of these relationships in association with learners' existing knowledge and experience within the problem domain. The complexity of the problem-solving task in FUMES was designed to reflect the nature of the real world problem, whereby success or failure was determined in accordance with the user's ability to reach a refuge chamber whilst considering environmental factors and relationships involving physical exertion and self-rescuer oxygen consumption (Chapter 4.3.2).

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Findings elicited from the FUMES implementation regarding the perceived uncertainty of the problem-solving context, perception of related entities within the problem domain, and recognition of problem complexity indicated that participants identified the complexity of the problem in accordance with their existing knowledge of the real world problem domain. Experienced Participants acknowledged the environmental context of problem-solving activity more readily than Novice Participants via their recognition of familiar physical characteristics and objects within the virtual mine. However, participants from both groups demonstrated an understanding of the complexity of the problem-solving task in terms of the relationships between movement speed, terrain inclination, physical effort, and oxygen consumption as they moved and interacted within the virtual mining environment. Participants also acknowledged the complexity of the problem-solving task in terms of multiple refuge chambers for evacuation, multiple possible outcomes, and the determinant nature of their actions in relation to the outcome of the problem-solving task. Interview responses further suggested that the complexity of the problem-solving task reflected that of the real world problem in that the layout of the mine, the available paths to refuge, and the environmental conditions needed to be considered during the process of determining a method for evacuation. In this manner, an understanding of the complexity of the problem-solving task promoted the development of strategies for achieving resolution.

This suggests that the complexity of the problem-solving task in FUMES was well situated in relation to the real world problem where participants were able to utilise their existing knowledge of relationships within the problem domain towards resolution. The experiential nature of problem-solving activity, where participants were free to choose their own path to refuge, contributed to their understanding of the relationships between movement speed, terrain inclination, physical effort, and oxygen consumption via direct action as they moved and interacted within the virtual mine. However, Novice Participants' inexperience with the Challenger mine resulted in greater problem complexity as they had to orientate and navigate within an unfamiliar environment. This was consistent with previous analysis suggesting that the solution method for the problem-solving task was too ill-structured for Novice Participants and that more information should have been provided during the problem statement in relation to navigation methods within the mining environment to address this deficiency (Chapter 7.2.1).

This indicates the need for the complexity of the problem-solving task to afford the existing contextually relevant problem-solving knowledge of the user in addition to embodying the situatedness of the real world problem. Analysis of the data collected during the FUMES

implementation indicates the following findings in relation to the complexity Situational Design Consideration:

- The complexity of the problem-solving task should account for the relationships within the real world problem domain that have a bearing on the outcome and represent them in a manner that is consistent with users existing contextually relevant knowledge. This requires clear and unambiguous feedback to be provided detailing the nature of these relationships such that their behaviour appears consistent with that encompassed by the real world problem. A problem-solving task involving the use of a crane to stack shipping containers would necessitate the use of visual feedback to denote the crane's position, and auditory feedback to denote when it was in motion, so that the relationship between the crane's controls and its actions were clear, for example, and;
- The complexity of the problem-solving task should reflect that of the real world problem in terms of the available solution paths, possible outcomes, and nature of the linkages between them. In practice, this means that the simulation environment should allow or restrict user behaviour according to the solution methods and outcomes pertinent to the real world problem in order for the problem-solving task to be well situated. However, the complexity of the problem-solving task must also be managed to ensure that it can be resolved by users in the event that their knowledge of the problem domain is inadequate. Scaffolding may be required to highlight solution paths, outcomes, and the nature of the linkages between them in order to reduce the complexity of the problem in this regard.

7.2.3 Domain Specificity

Domain specificity refers to the extent to which a problem is contextualised and may be characterised in accordance with the need for domain specific knowledge. The domain specificity of the problem-solving task in FUMES was designed to elicit participants existing knowledge of the real world problem domain by situating activity within a spatially accurate representation of the Challenger mine during an underground fire emergency. The virtual mining environment featured escape rises, refuge chambers, and visual cues such as depth markings, escape rise signs, and servicing infrastructure (Chapter 4.3.3). Participants were also provided with a cap-lamp and self-rescuer to assist them in reaching a refuge chamber.

The following sections detail the data analysis for domain specificity as a means of determining

the efficacy of this Situational Design Consideration within FUMES. This was undertaken according to evaluation criteria established from the literature (Table 2.15) pertaining to the perceived meaningfulness of the problem, the problem-solving strategies employed, and the extent to which the problem was contextualised.

Perceived Meaningfulness of the Problem

A series of three questionnaire prompts were employed using Experienced Participants and Novice Participants in order to gauge the meaningfulness of the problem in relation to the actions and knowledge required to achieve resolution (Figs. 7.58 through 7.60).

The training scenarios required me to do things that I would have to do during a real emergency evacuation of the Challenger mine
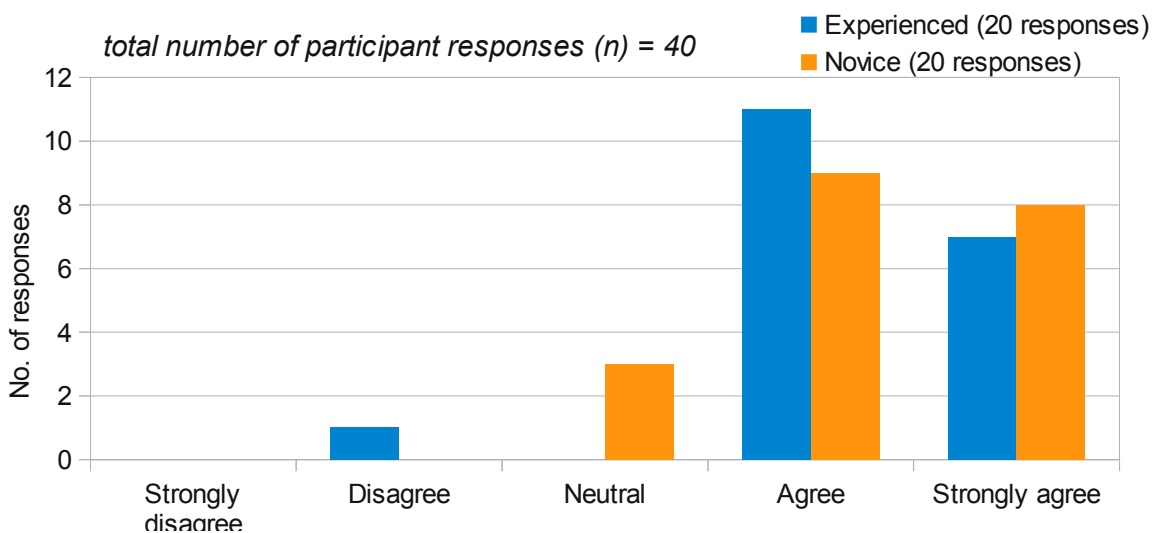
Figure 7.58. Extent to which actions required by the problem-solving task reflected those used during an emergency evacuation at Challenger

I needed to know the layout and structure of the Challenger mine in order to complete the training scenarios
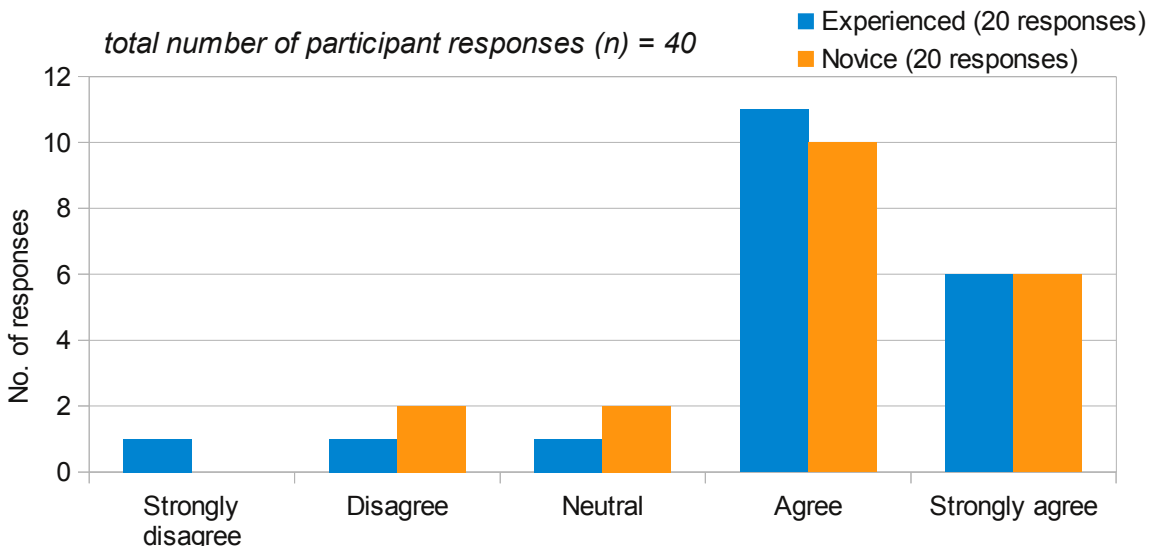
Figure 7.59. Extent to which knowledge of the layout and structure of the Challenger mine was required to resolve the problem-solving task

I needed to know the emergency evacuation procedures at Challenger in order to complete the training scenarios
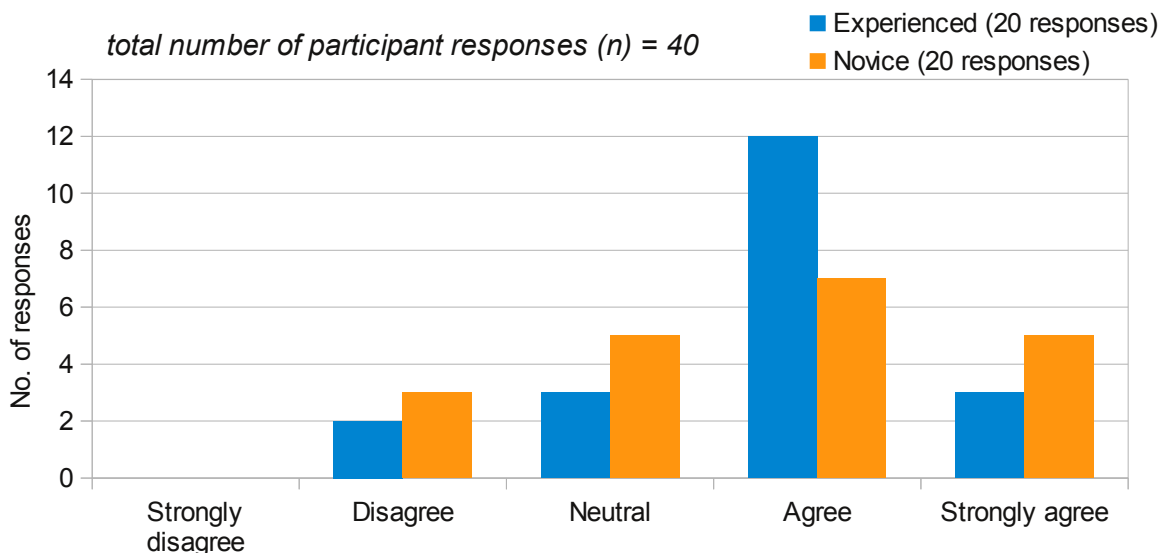
Figure 7.60. Extent to which knowledge of emergency evacuation procedures at Challenger was required to resolve the problem-solving task

Participants demonstrated that actions required to resolve the problem-solving task were consistent with those necessary during an evacuation at Challenger (Fig. 7.58). They further

established the need for knowledge of the layout and structure of the Challenger mine (Fig. 7.59), and the emergency evacuation procedures employed (Fig. 7.60), to resolve the problem-solving task.

Interview responses were elicited from four Experienced Participants and three Novice Participants in relation to whether the problem-solving task was worthwhile and meaningful. Feedback provided by both Experienced Participants and Novice Participants emphasised the value of the problem-solving task in terms of familiarising personnel with emergency evacuation scenarios in the Challenger mine:

- "It's probably good to have those scenarios as they are, because then people familiarise themselves with the work areas they could be entrapped in in a fire.";
- "Even though it's not a real life situation, if you ever got into an emergency situation, you'd feel like you'd done it before at least, you wouldn't start panicking.";
- "… it helps you understand more about the mine and what to do in an evacuation.", and;
- "They helped me out with what to expect when I'm under there "

Collectively, the questionnaire and interview responses demonstrated the meaningfulness of the problem-solving task in terms of familiarising personnel with the emergency evacuations of the Challenger mine. Resolving the problem-solving task relied upon knowledge and actions consistent with the requirements of emergency evacuations in the Challenger mine. This demonstrated the domain specificity of the problem-solving task in relation to the real world problem.

Problem-solving Strategies Employed

Previous analysis demonstrated that Experienced Participants were able to employ stronger, more specific problem-solving strategies than Novice Participants as a result of greater familiarity with emergency evacuations at Challenger (Chapters 7.1.2 and 7.1.4). Experienced Participants employed problem-solving strategies where they identified their proximity to hazards, determined the location of the nearest refuge chamber, and plotted the ideal route to take through the virtual mine. In contrast, the strategy utilised by Novice Participants predominantly focussed on orientation within the virtual mine. This highlighted the domain specificity of the problem-solving task, as knowledge of emergency evacuations at Challenger was needed for strong, domain specific problem-solving strategies to be viable.

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Extent to which Problem is Contextualised

Three questionnaire prompts were employed using Experienced Participants and Novice Participants in order to ascertain the extent to which the problem-solving task was contextualised or de-contextualised according to the time dependency of decision making (Fig. 7.61) and motivation to solve (Figs. 7.62 and 7.63).

I needed to make immediate decisions in order to complete the training scenarios
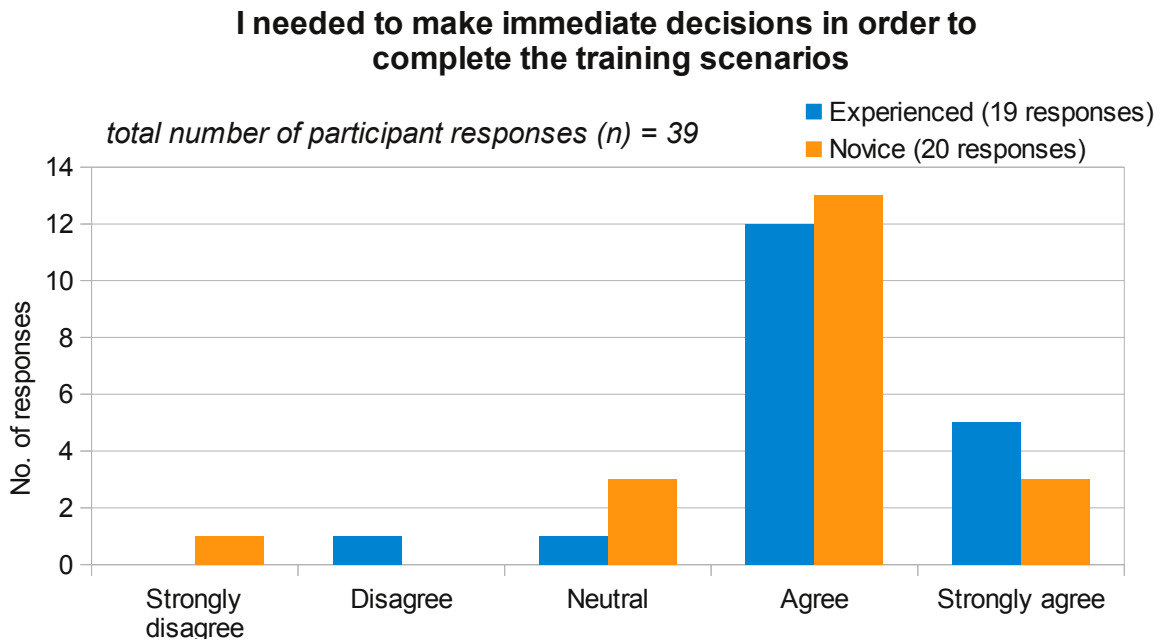
Figure 7.61. Need for immediate decision making to resolve the problem-solving task

I felt motivated to complete the training scenarios
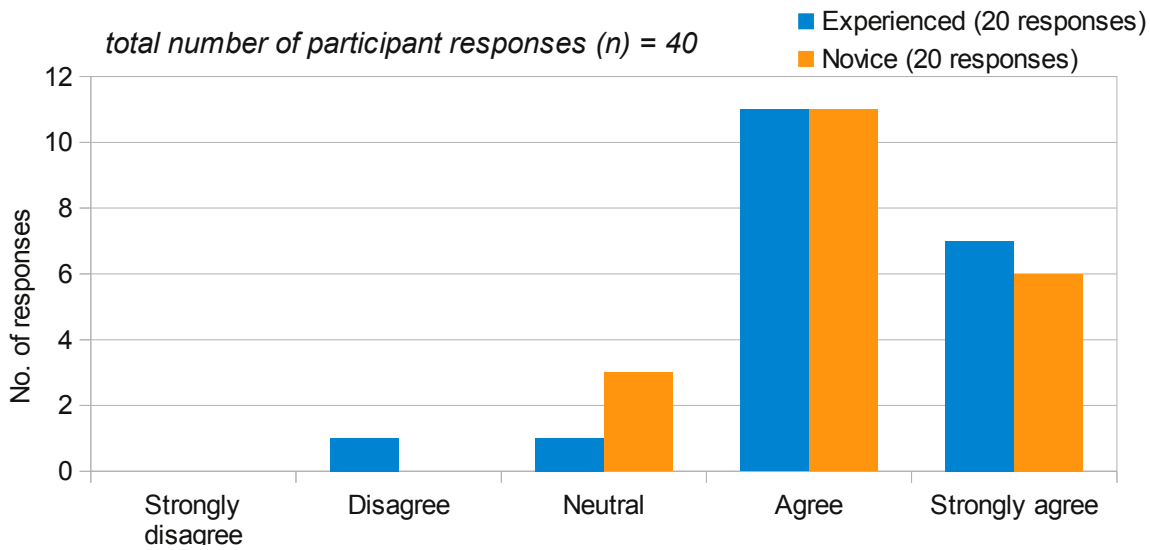
Figure 7.62. Extent of motivation for completing the problem-solving task

I felt a sense of urgency or excitement whilst completing the training scenarios
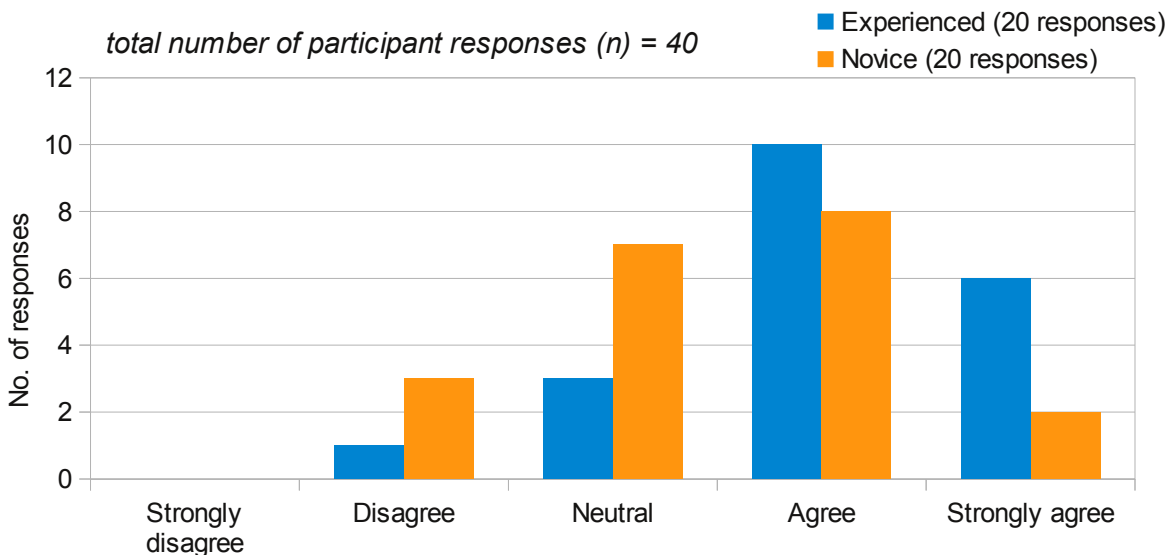
Figure 7.63. Extent to which participants felt a sense of urgency or excitement whilst undertaking problem-solving activity

Experienced Participants and Novice Participants clearly demonstrated that resolving the

problem-solving task required immediate decision making (Fig. 7.61). Whilst both groups of participants indicated that they felt motivated to complete the problem-solving task (Fig. 7.62), Experienced Participants demonstrated that they experienced sensations of urgency or excitement to a greater extent than Novice Participants (Fig. 7.63).

Four Experienced Participants and two Novice Participants were interviewed in relation to their motivation for completing the problem-solving task in FUMES. The responses provided by Experienced Participants demonstrated that they were more motivated than Novice Participants, citing not wanting to die or fail, a sense of novelty in comparison to more traditional training methods such as power-point presentations, and wanting to validate their existing knowledge of emergency evacuations at Challenger in case they were required to undertake an evacuation in the real world mine. In contrast, responses provided by Novice Participants, such as "it's good", and "I just thought I'd give it a go to see what it was like really, see if it was easy or hard, or what it was really like really", do not suggest the same sense of involvement or engagement.

The same participants were also queried as to the need for knowledge of the Challenger mine and its emergency evacuation procedures in order to resolve the problem-solving task. The responses provided by Experienced Participants indicate the necessity of knowledge relating to the mine layout, locations and functions of escape rises and refuge chambers, self-rescuer application, and the evacuation process, but tend to de-emphasise the significance of first hand experience within the mining environment:

- "I don't think you would have to know a great deal about it, as long as you knew the basics … know what escape ways are, and you know what refuge chambers are, you can pretty well find where they are.";
- "I don't think you would need to know the mine all that well. If you've got the basic principles which are move down to a refuge chamber, use a self-rescuer if you need it, there's not a lot more to it really than that.", and;
- "I think you would have to have a little bit of knowledge, if not just Challenger, knowledge of decline mine, because you're twisting and turning around this path and then every twenty metres you pull off a level and you've got escape rises just in your levels or just off the decline going up to the next one. So it's kind of one of those things you need to get your head around a little bit. Even just a little bit of experience having been down there would help, because if it was the first time you looked at it, you probably wouldn't really know what you were doing."

In contrast, Novice Participants placed greater emphasis on the need for first hand experience within the Challenger mine and a solid understanding of the emergency evacuation process:

- " … if you went over the evacuation plan and someone told you were the refuge chambers were and you knew where you were at the start, and you walked to the escape way ...", and;
- "I reckon they should be able to spend a swing underground, that would be good for them as far as the simulator was concerned. Probably about four shifts, so they get orientated with getting down, getting up, and seeing where things are."

The four Experienced Participants were further queried to whether the method used for resolving the problem-solving was acceptable given their experience at Challenger. Responses from all four Experienced Participants indicated the solution method reflected actions that would be taken to reach a refuge chamber during an evacuation in the real world mine.

Collectively, the questionnaire and interview responses demonstrated the highly contextualised nature of this problem-solving task in relation to the real world problem. Experienced Participants and Novice Participants indicated the problem-solving task required immediate decision making and provided them with sufficient motivation, although Experienced Participants experienced a greater sense of urgency and excitement. This was reflected in interview responses detailing participants' motivation, where Experienced Participants cited a desire to succeed to validate their existing knowledge of emergency evacuation procedures at Challenger, and the novelty of FUMES as a training platform. Interview responses from both groups of participants indicated a clear need for domain specific knowledge in order to engage with the problem-solving task, but Novice Participants placed greater emphasis on first hand experience in the Challenger mine than Experienced Participants. Experienced Participants also indicated that the method used for resolving the problem-solving task was compatible with actions undertaken during a real world emergency evacuation, further demonstrating the highly contextualised nature of the problem-solving activity.

Summary for Domain Specificity

The domain specificity of the problem-solving task delineates the degree to which knowledge of the real world problem domain is required in order to facilitate resolution. The problem-solving task in FUMES was designed to be very domain specific, situating activity within an accurate

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representation of the Challenger mine in which participants were required to seek refuge in response to an underground fire emergency in accordance with established real world evacuation protocols (Chapter 4.2.3)

Findings elicited from FUMES regarding the perceived meaningfulness of the problem, the problem-solving strategies employed, and the extent to which the problem was contextualised indicated that the problem-solving task was highly domain specific in relation to emergency evacuations of the Challenger mine. Experienced Participants and Novice Participants indicated that the problem-solving task was a viable means by which to familiarise personnel with emergency evacuations at Challenger as it relied on knowledge and actions consistent with a real world emergency. Experienced Participants employed stronger, more domain specific problem-solving strategies than Novice Participants due to their more extensive knowledge of emergency evacuations at Challenger, whereby they identified their proximity to hazards, determined the location of the nearest refuge chamber, and plotted the ideal route to take through the virtual mine in order to reach it. Participants from both groups indicated that the problem-solving task required them to make immediate decisions and was a motivating factor, but this was more pronounced for Experienced Participants whose desire to succeed was based on the need to validate their existing knowledge of emergency evacuation procedures at Challenger. Domain specific knowledge pertaining to the layout of the mine, the locations and functions of escape rises and refuge chambers, self-rescuer application, and the evacuation process was identified as being necessary in order to engage with the problem-solving task. However, Novice Participants placed greater emphasis on the need for first hand experience within the Challenger mining environment than Experienced Participants.

This suggests that the domain specificity of the problem-solving task in FUMES effectively delineated the situatedness of the real world problem where participants were able to utilise existing contextually relevant knowledge. The problem-solving task was meaningful to participants as it familiarised them with emergency evacuations in the real world Challenger mine. Experienced Participants effectively employed strong, domain specific problem-solving strategies, which suggested that their actions, and the objects they could act upon, were consistent with those used during a real world evacuation. The greater sense of urgency, excitement, and motivation reported by Experienced Participants, in addition to their desire to validate their existing knowledge within the simulator, suggested a greater appreciation of the real world problem in terms of the potential for serious injury or death if safe and effective evacuation could not be carried out during an emergency. This demonstrated that the simulation

environment was suitably domain specific such that participants could reliably test their existing contextually relevant knowledge with the expectation that the outcome would be consistent with the real world problem.

This indicates the need for the domain specificity of the problem-solving task to afford the existing contextually relevant problem-solving knowledge of the user in addition to embodying the situatedness of the real world problem. Analysis of the data collected during the FUMES implementation indicates the following findings in relation to the domain specificity Situational Design Consideration:

- The domain specificity of the problem-solving task needs to establish links to the real world problem in order for the problem to be perceived as meaningful. When designing, this means that objects, actions, and environmental characteristics relevant to the real world problem need to be identified and then instantiated within the 3D simulation environment as aspects that have a bearing on problem-solving activity. In the event that users' knowledge of the problem domain is lacking, additional information may need to be provided during the problem statement to establish the significance of these objects, actions, and environmental characteristics so that the domain specificity of the problem-solving task has value;
- The domain specificity of the problem-solving task needs to accommodate the strategies used to solve the real world problem. This requires the user to be provided with the same means to resolve the problem-solving task as per the real world problem during design, and;
- The domain specificity of the problem-solving task needs to provide users with a reliable means to validate their existing contextually relevant knowledge in relation to real world problem resolution. In practice, this means that the domain specificity of cause / effect relationships need to be preserved so that users can test their understanding of the problem domain. A problem-solving task requiring users to fly an aeroplane would necessitate the functions of the flight controls to be consistent with their real world counterparts, for example.

7.2.4 Problem Representation

Problem representation influences the way problem-solvers perceive a problem, isolate

important from irrelevant information, and represent it internally. The problem-solving task was presented as a three-dimensional depiction of the real world problem where users needed to undertake emergency evacuation procedures within a spatially accurate representation of the Challenger mine (Chapter 4.3.4). Users were afforded the ability to move and orientate freely within the virtual mine and could utilise escape rises, the cap-lamp, and the self-rescuer at their discretion. In order to expose participants to a variety of potential evacuation scenarios, the problem-solving task was organised into a series of three distinct problem-solving instances. Each instance was more ill-structured, complex, and domain specific than the one that preceded it, requiring the user to assume increasing responsibility for their learning and the acquisition of learning resources. The problem statement was expressed using a sequence of information statements which explicitly identified the context of the problem, the goal of the problem, and the methods available to them for interaction. Participants were then free to acquire information from a variety of sources within the virtual mining environment, by which they could identify their position, proximity to hazards, and the location of the closest refuge chamber by moving around and manipulating their viewing perspective.

The following sections detail the data analysis for problem representation as a means of determining the efficacy of this Situational Design Consideration within FUMES. This was undertaken according to evaluation criteria established from the literature (Table 2.15) pertaining to the perception of the problem representation, identification of relevant problem features, identification of relationships, and the problem-solving strategies employed.

Perception of the Problem Representation

During interview, four Experienced Participants and three Novice Participants were asked to describe the information they acquired at the onset of the problem-solving task. Responses indicated that Experienced Participants perceived the problem-solving task as one in which information was provided explicitly, but also required information to be gathered via interaction within the virtual mining environment:

- "You got a run down on what is was that was triggering the emergency … and then you have to figure out where you are in the mine, and what you're going to do.";
- "The information that I was aware of was what was going on, the fire, where it was, if it was in the decline below 780 level, and then the other information you could find yourself by all the signage that was on there.";

- "I remember there was something in the headphones, some instructions given in the headphones." and;
- "Straight away I could hear the personal radio saying emergency and the instructions."

Conversely, responses provided by the Novice Participants did not emphasise an active role in the acquisition of information within the virtual mining environment to the same extent as Experienced Participants. However, their responses did suggest awareness of information provided explicitly during the problem statement which informed them that an emergency had been declared, and the need to get to a refuge chamber:

- " … there's an emergency and you need to get to a refuge chamber.", and;
- "The program explained what you had to do. I had the cross section of the mine diagram on a piece of paper which showed where everything was, so I knew if I was on level 760 I could go up to the next refuge chamber or down or whatever."

The same participants were also asked to describe the initial state of the problem-solving task within FUMES. Responses provided by participants from both groups acknowledged the auditory cues which were used to communicate the nature of the emergency, but noted that this information was not always clearly understood as it was only specified once at the immediate onset of problem-solving activity. Responses provided by Experienced Participants further suggested that the way in which emergency information was provided by these auditory cues was not entirely consistent with the operation of the emergency radio system during a real world evacuation:

- "I couldn't really hear him much, the bloke who talks, I'm not sure if he said anything else or if he just said get to the nearest refuge chamber and it was an emergency.";
- The start was a little bit quick, you'd push the go button and then as soon as you appeared there you were getting all of that information in one hit. A lot of the time, there's that much noise around the environment, you don't always get the information so quickly and in one hit. Like it might take a couple of times to hear the radio say 'Emergency. Emergency. Emergency', because we don't have any red lights on our machines or that sort of thing. Some of the information came a little too quick.", and;
- "Short. I distinctly remember getting caught up thinking about one, hitting the button too quickly and then the scenario had started, and I wasn't really sure what the emergency was … there wasn't the ability for the person to go 'oh, I missed the

emergency, what was it again?' … they have an automated radio system here that will keep telling you that an emergency is going on until the radio system is switched off. It keeps repeating every 45 seconds."'

These interview responses reveal that the problem representation did not explicitly instruct participants to determine their position and identify the circumstances of the emergency at the onset of the problem-solving task. Experienced Participants, who were familiar with emergency evacuations of the Challenger mine, actively determined this information within the virtual mine, which suggests that the manner in which the problem was represented was well situated in relation to the real world problem. Conversely, Novice Participants, who had limited knowledge of emergency evacuation procedures at Challenger, did not recognise the importance of orientating themselves and identifying their proximity to hazards as part of the evacuation process. As such, this implies that Novice Participants would experience greater uncertainty in relation to determining an effective route through the virtual mine to refuge, which is consistent with previous analysis demonstrating that the solution method was unfamiliar and ill-structured for Novice Participants (Chapter 7.2.1). Participants descriptions of the problem representation indicated that information explicitly provided via auditory cues was not always clearly understood as participants were unprepared and faced interference from other audio sources within the virtual mining environment.

Identification of Relevant Problem Features

Previous interview responses demonstrated that Experienced Participants were more adept at identifying relevant problem features than Novice Participants due to their better developed knowledge of the problem domain (Chapter 7.1.2). Experienced Participants identified their proximity to the obstruction or emergency, the location of the nearest refuge chamber, and the ideal route to take through the virtual mine as relevant problem features. In contrast, Novice Participants identified the layout and structure of the virtual mine, including salient spatial cues, as relevant considerations during problem-solving activity. Novice Participants were limited in their ability to consider more significant features due to a deficiency in domain knowledge relating to spatial awareness.

These interview responses infer that both Experienced Participants and Novice Participants identified relevant problem features during interaction within the virtual mining environment.

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This suggests that the problem representation encouraged the identification of relevant problem features via experiential interaction, where participants were free to move and orientate their viewing perspective within the 3D environment in order to acquire information. However, Novice Participants lack of domain knowledge inhibited their ability to identify relevant problem features to the same extent as Experienced Participants. This demonstrates the need for the provision of additional information during the problem statement in order to accommodate this deficiency.

Identification of Relationships

Experienced Participants were more effective at identifying relationships between entities within the problem domain, but that the nature of the relationships between physical effort and movement, physical effort and breathing, and physical effort and oxygen consumption were recognised consistently by participants from both groups (Chapter 7.1.3). The descriptions provided by participants during interview suggest that they were deriving their understanding of these relationships as they were moving through the virtual mining environment:

- " … you can see your heart rate, and you know by walking up and down declines and climbing ladders you know what exertion goes into it ...";
- " … when I tried to speed up and move faster, you could hear your breathing increase and therefore got the impression that you were exerting yourself more.";
- "At one stage I went uphill and it appeared to be, I think, again heavier breathing and you were moving and exerting more energy.";
- "If you were climbing a ladder it took a bit longer. If you were walking up the decline or walking down the decline you could tell the difference that you were breathing different.", and;
- " … if you going up an access ladder of whatever you could hear yourself really breathing heavy."

This implies that the experiential nature of the problem representation served to develop participants' understanding of related entities within the problem domain. Participants were free to traverse the decline and climb escape rises within the mining environment and in doing so, develop their understanding of relationships via the association of their actions with the feedback that was provided.

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Problem-solving Strategies Employed

Experienced Participants formulated stronger problem-solving strategies than Novice Participants as a result of their more extensive knowledge of the problem domain (Chapter 7.1.4). The problem-solving strategies employed by Experienced Participants identified their proximity to hazards, the location of the nearest refuge chamber, and the ideal route to reach it through the virtual mine. In contrast, the problem-solving strategies utilised by Novice Participants predominantly focussed on orientation within the virtual mine due to lack of knowledge of the spatial characteristics of the Challenger mining environment.

The problem representation afforded participants the freedom to determine their method for evacuation in terms of the path that they took through the virtual mine to refuge, and the circumstances under which they utilised escape rises, their cap-lamp, and their self-rescuer. Whilst Experienced Participants demonstrated that they were capable of developing strong problem-solving strategies in accordance with this type of problem representation, Novice Participants lacked the necessary domain knowledge to develop strong problem-solving strategies without guidance (Chapter 7.1.4). This suggests that the problem representation was too open-ended and unstructured for Novice Participants and that more information detailing the spatial characteristics of the Challenger mine needed to be provided prior to entering the virtual mine.

Summary for Problem Representation

The technical capabilities of 3D simulation environments allow problems to be represented in a manner that is consistent with real world problem scenarios whilst also providing the flexibility to provide additional visual and auditory information to supplement the learning process. The problem-solving task in FUMES was represented as a series of three problem-solving instances which became progressively more ill-structured and complex by virtue of the successive omission of information provided during the problem statement (Chapter 4.3.4). Participants were required to negotiate a three-dimensional depiction of the Challenger mining environment during an underground fire emergency to determine their means of evacuation in accordance with established real world procedures.

Findings elicited from the FUMES implementation regarding the perception of the problem

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representation, identification of relevant problem features, identification of relationships, and the problem-solving strategies employed demonstrate that the problem representation was well suited to the development of contextually relevant knowledge within an environment of practice. Experienced Participants recognised the problem-solving task as one requiring them to complement the information provided explicitly during the statement of the problem with information they acquired themselves regarding their position and the circumstances of the emergency within the virtual mine. However, Novice Participants lacked familiarity with emergency evacuation procedures at Challenger and needed to recognise the importance of gathering this information themselves without being prompted. Participants from both groups also indicated that some information provided during the statement of the problem, specifically the auditory cues used to communicate the nature of the emergency, were not always clearly understood. These auditory cues were only played once at the onset of problem-solving activity and were sometimes obscured due to interference from other auditory cues within the virtual mining environment. The problem representation was found to encourage the identification of relevant problem features and develop participants' understanding of related entities within the problem domain by affording participants the ability to move freely and interact at their discretion within the virtual mine. Participants were free to determine the means by which they evacuated from the virtual mine in terms of the route they took to refuge, and the circumstances under which they utilised escape rises, their cap-lamp, and their self-rescuer towards this goal. However, Novice Participants lacked the necessary domain knowledge required to identify relevant problem features to the same extent as Experienced Participants which inhibited their ability to develop strong, domain specific problem-solving strategies.

This suggests that the 3D simulation environment provided an effective means by which to represent the real world problem. The problem-solving task was well situated within an authentic environment which resembled the Challenger mine during an emergency evacuation and facilitated experiential interaction via the provision of immediate response to participant input. Both Experienced Participants and Novice Participants were able to familiarise themselves with potential emergency evacuation scenarios within the Challenger mine via a series of problem-solving instances which varied in accordance with the environment conditions present within the virtual mine and the amount of information explicitly provided during the statement of the problem. However, the inability of Novice Participants to formulate strong problem-solving strategies, identify significant problem features, and acquire information of their own volition at the onset of problem-solving activity demonstrated that participants' knowledge of the domain affected their ability to engage with the problem representation. This

indicated the need for additional information to be provided during the problem statement in order for Novice Participants to have the requisite knowledge of the domain required to engage with the problem representation with the same effectiveness as Experienced Participants. Furthermore, the auditory cues utilised during the problem statement should have been made accessible to participants such that they could review them again at their discretion in the event that they were not clearly understood.

This indicates the need for the problem representation to afford the situatedness of the real world problem using the capabilities afforded by 3D simulation environments. Analysis of the data collected during the FUMES implementation indicates the following findings in relation to the problem representation Situational Design Consideration:

- The information provided during the problem statement should be presented in sequence where any pre-requisite requirements for knowledge are addressed before the next piece of information is made available. During design, this means that information which forms the basic foundation of the problem statement should be presented first, before moving on to the exposition of more complex or specific information so that users can develop their understanding of the problem using each piece of information in turn. For example, a problem-solving task requiring users to use a virtual crane to stack a collection of containers could be expected to provide information detailing the controls of the crane before divulging the order in which the crates needed to be stacked;

- The problem representation should be designed to allow users to enact the solution method experientially in order to encourage the identification of relationships and relevant features within the problem domain. This entails utilising the technical capabilities of 3D simulation environments to provide users the ability to resolve the problem-solving task freely and at their discretion using the methods of interaction available to them;

- The problem representation should provide means for the user to refer back to the information provided during the problem statement. In practice, this means providing users with the ability to review this information within the 3D simulation environment at their discretion. A button input could be used to trigger an on-screen display which reiterated the information detailed during the problem statement, for example, and;

- The problem representation may be organised as a series of distinct problem-solving instances in order to provide greater exposure to potential diversity in the real world

problem. The user should be presented with a collection of problem-solving activities embodying the same basic characteristics whilst providing some variation in terms of information explicitly provided or obstacles to completion that are encountered.

7.2.5 Authenticity of Information

Information presented during the problem statement needs to be authentic with respect to the real world problem being modelled to encourage transfer and application of knowledge. The problem statement was designed to be authentic in relation to the real world problem both in terms of information provided and the medium utilised to present it (Chapter 4.3.5). To this end, auditory cues were employed under the guise of a personal radio to replicate the emergency evacuation broadcast system used at Challenger. The auditory cues informed users of an emergency in response to observations of smoke and advised them to evacuate to refuge. They also provided additional information at the onset of the first two problem-solving instances detailing participants' initial location and the nearest refuge chamber. The auditory cue presented at the beginning of the third problem-solving instance omitted this information and did not inform participants' of the exact location of smoke within the mine.

The following sections detail the data analysis for authenticity of information as a means of determining the efficacy of this Situational Design Consideration within FUMES. This was undertaken according to evaluation criteria established from the literature (Table 2.15) pertaining to the consistency of information.

Consistency of Information

Four Experienced Participants were asked during interview to evaluate whether the information provided via auditory cues during the statement of the problem was consistent with the information which would be provided during an emergency evacuation scenario at Challenger:

- "Yep, yep, it is if it is on channel two, but when we get to a refuge chamber we go to channel one for the emergency channel.";
- "I think so, I mean the guys are only going to get what they need to know, they're not going to get the inner most workings of an emergency ...", and;
- "Yes definitely, you're listening to the emergency thing which gets played over the radio

and you've got an instruction, and that is definitely what happens."

These responses suggest that the auditory cues were employed in a manner that was consistent with the emergency broadcast system used at Challenger to notify personnel of an evacuation. However, one Experienced Participant noted that not all personnel at Challenger would have access to a personal radio during an emergency:

- "A lot of us don't have hand-helds, we have radios on our machines. Once you leave your machine, you don't have any communication until you make it to another machine or to a refuge chamber. If you do have a hand held, then it's all well and good, but a lot of the time we only have fixed radios."

Collectively, these interview responses demonstrate that the information provided during the problem statement was consistent with the information that would be available at the onset of the real world problem. Experienced Participants acknowledged the use of auditory cues as an authentic means by which to present the information which would be disseminated by emergency radio broadcast during an emergency at Challenger, despite the fact that not all personnel would be outfitted with a personal radio during a real world emergency evacuation scenario at Challenger.

Summary for Authenticity of Information

The information provided during the problem statement needs to be authentic with respect to previous problem-solving experience in order to facilitate the transfer of knowledge. To this end, auditory cues were employed under the guise of a personal radio during the problem statement as a means of replicating the function of the emergency broadcast system used at Challenger during an evacuation (Chapter 4.3.5).

Findings elicited from the FUMES implementation regarding the consistency of information provided during the problem statement demonstrate that the auditory cues served as an authentic means by which to disseminate information. Experienced Participants indicated that auditory cues were employed in a similar manner to the emergency broadcast system used at Challenger to inform them when an evacuation of the mine had been ordered. However, one Experienced Participant pointed out that not all personnel would have access to a personal radio during real world emergency evacuation scenarios at Challenger.

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This suggested that the technical capabilities afforded by 3D simulation environments provided an authentic means by which to present information within the problem statement to participants. The auditory cues employed to impart information appealed to Experienced Participants' existing knowledge of the emergency broadcast system used at Challenger, despite the fact that not all personnel carried personal radios within the real world mine. This was consistent with previous analysis which demonstrated Experienced Participants' ability to identify the significance of the information provided during the problem statement and utilise it in conjunction with their existing contextually relevant knowledge to effect resolution (Chapter 7.1.2). Novice Participants were not as effective in this regard due to a lack of contextually relevant domain knowledge (Chapter 7.1.2), despite the fact that the auditory cues provided more information than what would be provided by the emergency broadcast system during an emergency. Previous analysis indicated that Novice Participants needed to be provided with more information during the statement of the problem (Chapter 7.2.1), suggesting that the authenticity of the information provided in relation to the real world problem could be sacrificed in order to better enable Novice Participants to achieve resolution.

This indicates the need for the authenticity of information to accommodate the situatedness of the real world problem via the technical capabilities of the 3D simulation environment. Analysis of the data collected during the FUMES implementation indicates the following findings in relation to the authenticity of information Situational Design Consideration:

- The problem statement should provide more information than the real world problem statement if users' knowledge of the problem domain is inadequate. The authenticity of information in the problem statement can thus be ceded in the interests of providing a more well-structured problem with less uncertainty. As an example, a problem-solving task requiring medical students to respond to a virtual emergency room scenario might identify the nature of the patient's injuries for them, even though this information would not be explicitly provided during a corresponding real world problem scenario;
- The problem statement should be presented in a manner that is consistent with the real world problem statement. This entails making use of the visual and auditory capabilities of the 3D simulation environment to replicate the means by which information would be acquired during the real world statement of the problem. A virtual drill instructor might be employed to inform users that they were required to identify and clear a 3D model of a jammed rifle, for example;

7.2.6 User Control

The technical capabilities of 3D simulation environments can be used to provide users' with methods of interaction that approximate the actions that would be undertaken during real world problem-solving activity. User control mechanisms implemented within the 3D simulation environment were designed to provide participants with the ability to look and orientate themselves within the virtual mining environment, with added abilities included for climbing escape rises, equipping their self-rescuer, and changing the beam intensity on the cap lamp (Chapter 4.3.6).

The following sections detail the data analysis for user control as a means of determining the efficacy of this Situational Design Consideration within FUMES. This was undertaken according to evaluation criteria established from the literature (Table 2.15) pertaining to the support for movement and interaction, perceived sense of presence, and quality of collision detection.

Support for Movement and Interaction

Two question prompts were utilised to gauge the effectiveness with which Experienced Participants and Novice Participants could move and interact within the 3D simulation environment (Figs 7.64 and 7.65).

I was able to effectively interact with objects within the 3D environment
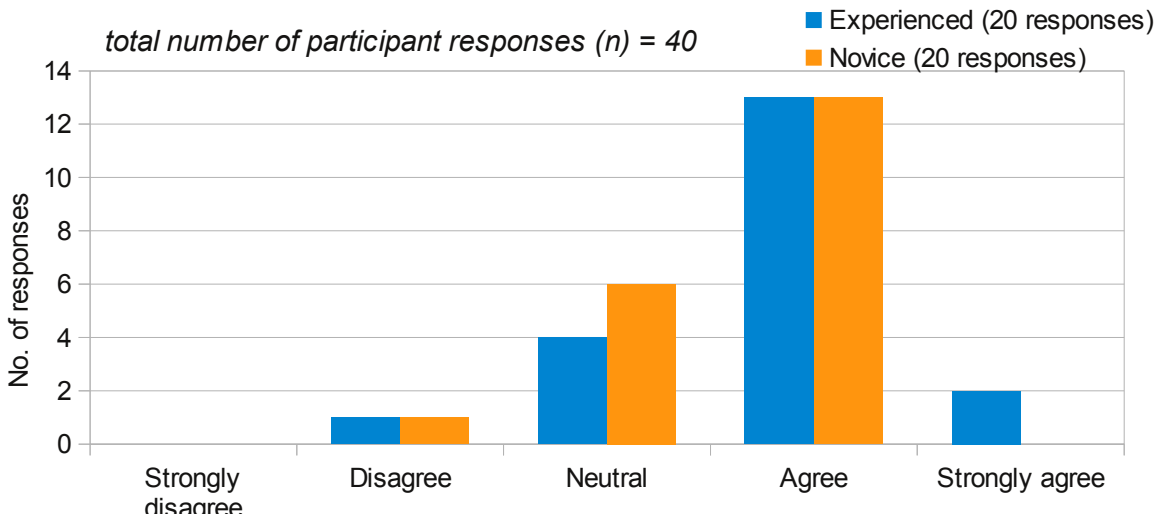
Figure 7.64. Effectiveness with which objects could be interacted with within the 3D simulation environment

The keyboard and mouse allowed me to move and interact effectively within the 3D environment
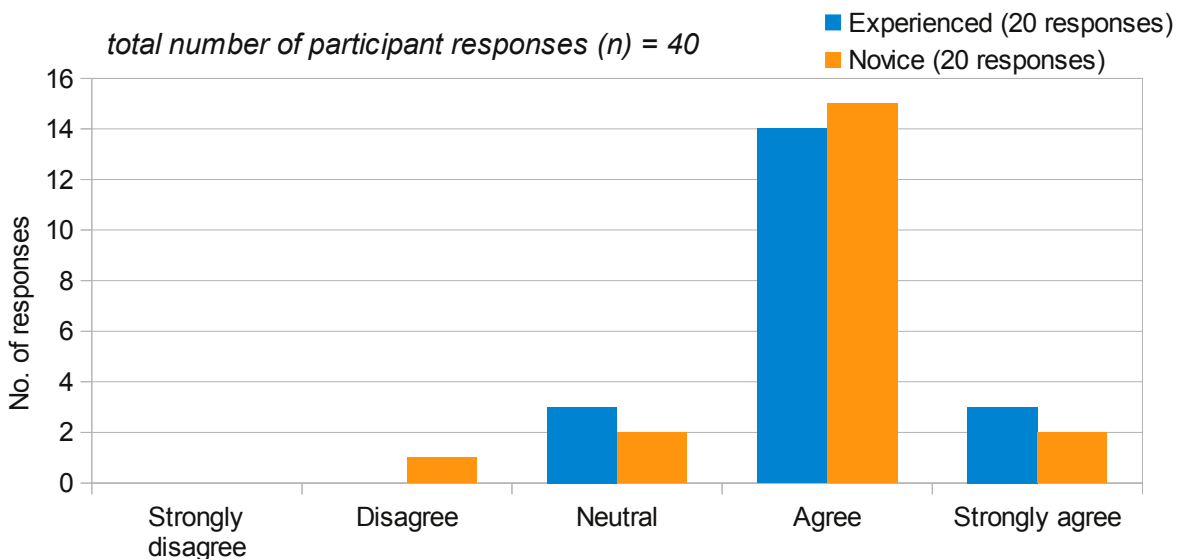
Figure 7.65. Effectiveness with which the keyboard and mouse could be used to move and interact within the 3D simulation environment

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Both Experienced Participants and Novice Participants indicated that they were effectively able to move and interact with objects within the 3D simulation environment using the keyboard and mouse (Figs 7.64 and 7.65).

This was consistent with interview responses elicited from four Experienced Participants and three Novice Participants in relation to how well they were able to move and interact within the simulation, and if they felt there were any limitations to doing so. Participants' responses emphasised that the controls afforded them the freedom to dictate their approach to problem-solving activity:

- "I could do whatever I wanted to whenever.";
- "If you wanted to do something you could pretty much do it straight away, pretty easily.", and;
- "No, I don't think there were any barriers , I was able to go up any ladders I wanted to, or go into a level and walk up and down the decline. Yeah it was fine."

Collectively, the questionnaire and interview responses indicated that both Experienced Participants and Novice Participants were afforded effective control of their movement and interaction within the simulation environment via keyboard and mouse input. This afforded them the ability to freely determine the sequence of actions to be undertaken in order to resolve the problem-solving task.

Perceived Sense of Presence

Participants did not report a persistent sense of presence during their time within the 3D simulation environment, but this did not impede their ability to complete the problem-solving task (Chapter 7.1.7). However, one Experience Participant did report that the ability to move and interact effectively within the virtual mining environment facilitated a sense of presence.

Quality of Collision Detection

The quality of collision detection within the simulation environment was assessed using two questionnaire prompts with Experienced Participants and Novice Participants (Figs. 7.66 and 7.67).

I knew when I had walked or run into objects within the 3D environment
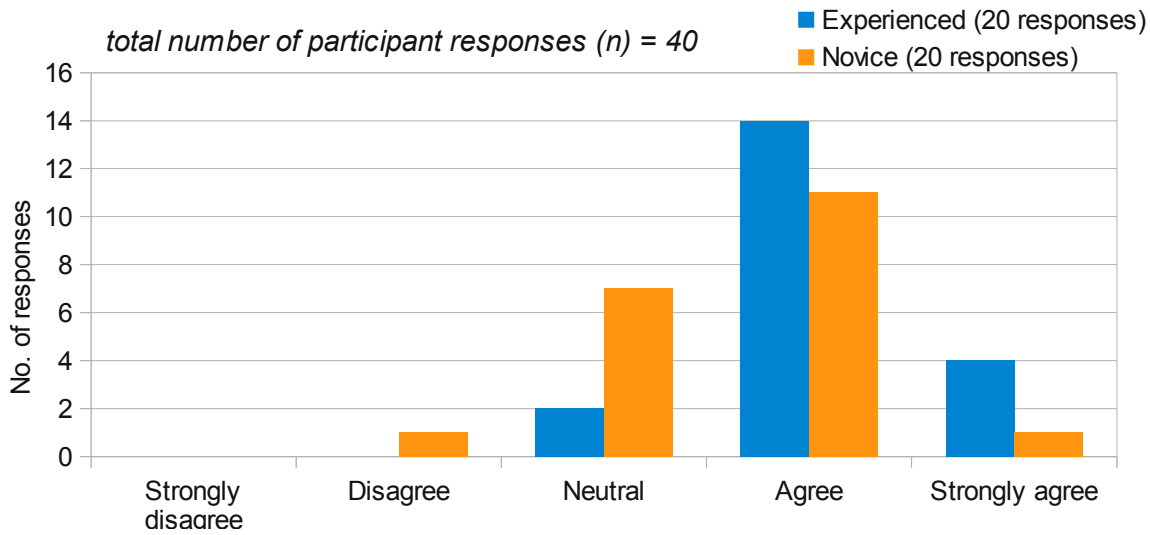
Figure 7.66. Extent to which participants knew when they had collided with objects within the 3D simulation environment

I knew when my movement was obstructed by a solid object within the 3D environment
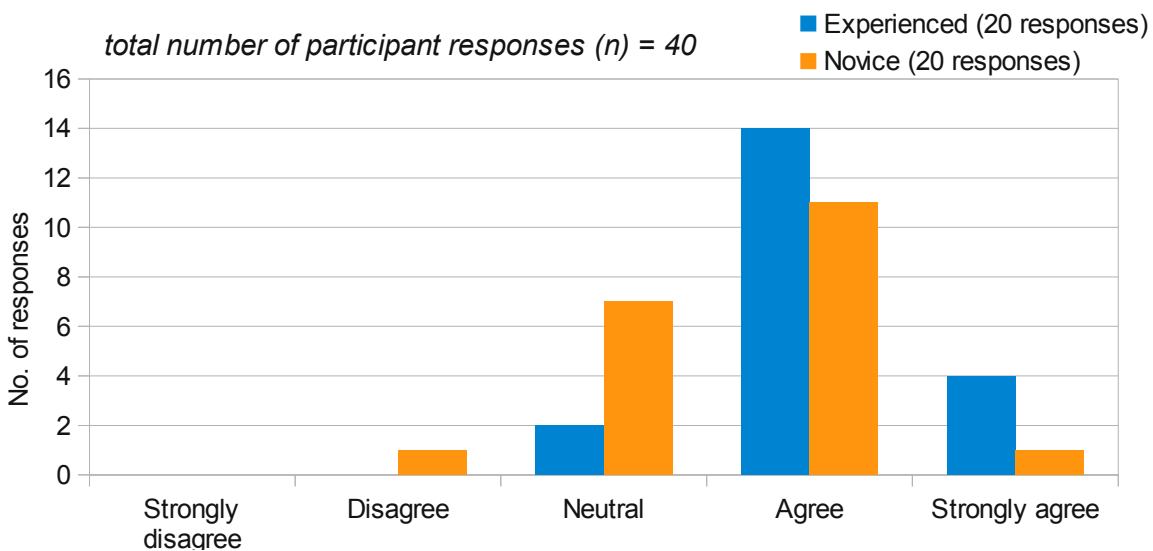
Figure 7.67. Extent to which participants knew when their movement was obstructed by an object within the 3D simulation environment

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While both groups of participants tended to know when they had collided with objects (Fig 7.66), and when their movement was obstructed by objects (Fig 7.67), this was more evident for Experienced Participants than Novice Participants.

This suggested that the quality of the collision detection within the 3D simulation environment was sufficient to allow participants to identify solid objects which could obstruct movement within the virtual mine. However, Experienced Participants were better able to identify objects which could obstruct movement, suggesting the presence of further developed environmental awareness within the virtual mining environment.

Summary for User Control

3D simulation environments can provide mechanisms of control which approximate those used during real world problem-solving activity to engage users in the learning process. Participants in FUMES were provided with mechanisms for control analogous to actions utilised during emergency evacuation of the Challenger mine, where they could walk, run, orientate their viewing perspective, climb escape rises, change their cap lamp beam setting, and equip their self-rescuer within the virtual mining environment (Chapter 4.3.6).

Findings elicited from the FUMES implementation regarding the support for movement and interaction, perceived sense of presence, and quality of collision detection demonstrated that participants were provided with adequate control mechanisms within the 3D simulation environment. Both Experienced Participants and Novice Participants indicated that the keyboard and mouse provided effective control of their movement and interaction such that they were free to dictate their approach to the problem-solving task. Participants were able to effectively engage in problem-solving activity, but adequate control alone was not sufficient to engender a persistent sense of presence within the virtual mining environment. The quality of the collision detection afforded participants the ability to identify solid objects which could obstruct movement within the virtual mine. However, this was more evident for Experienced Participants which suggests that they had better environmental awareness within the virtual mine.

This implies that the technical capabilities afforded by 3D simulation environments provided participants the ability to effectively engage with the problem-solving task in a manner that was consistent with the real world problem. Participants were able to utilise their existing knowledge of emergency evacuation procedures at Challenger in accordance with the control mechanisms

that were provided to undertake actions within the simulation environment which reflected those which would be employed during a real world emergency. Participants were thus able to exercise control at their discretion to determine the sequence of actions to be undertaken in order to resolve the problem-solving task. The obstacles to effective control were clearly identifiable as a result of adequate collision detection within the simulation environment and appealed to participants existing knowledge of potential obstacles within the real world mine.

This indicates the need for the control mechanisms to appeal to user's existing knowledge of the problem domain using the capabilities afforded by 3D simulation environments. Analysis of the data collected during the FUMES implementation indicates the following findings in relation to the user control Situational Design Consideration:

- Users should be provided with control mechanisms that approximate the actions used to resolve the real world problem in order to appeal to their existing knowledge of the real world problem. During design, this means marrying real world actions to appropriate control mechanisms using the technical capabilities of the 3D simulation environment;
- The control scheme should provide users with the freedom to interact at their discretion in order to reflect the experiential nature of real world problem-solving activity and contribute to the perception of presence. The design should allow users to choose where and when they wish to initiate interaction using the control mechanisms provided to them, and;
- The obstacles to user control within the simulation environment need to be clearly identifiable and reflect those present within the real world problem. In practice, this requires the selected software platform to have adequate capability for determining when collisions between the user and other objects occur such that objects appear solid and act as impediments to movement.

7.3 Problem-based Learning Design Principles

Problem-based Learning Design Principles act as core tenants and drive the learning process within the 3D simulation environment. The characterisation of these principles occurs in conference with the Situational Analytical Factors and Situational Design Considerations which have been established (Chapter 2.5). The role of Problem-based Learning Design Principles during the FUMES implementation and their validity as design considerations is explored in the

following sections:

- Chapter 7.31 examines feedback;
- Chapter 7.3.2 scrutinises assessment;
- Chapter 7.3.3 appraises information;
- Chapter 7.3.4 explores learner control, and;
- Chapter 7.3.5 investigates reflection.

7.3.1 Feedback

Problem-based learning environments provide feedback in response to learner interaction in order to guide their search for a solution to the problem. Feedback was provided within the 3D simulation environment at both the facilitator and task environment level, where auditory cues presented under the guise of personal radio communications were used to approximate a facilitator construct, while feedback provided by the task environment was incorporated into the 3D simulation environment itself (Chapter 4.4.1). Auditory cues presented by the personal radio facilitator construct were used to inform or warn participants of specific occurrences within the virtual mining environment and were also used to question their actions and behaviour. The dynamic rendering characteristics of the 3D simulation environment were used to provide immediate and uninterrupted visual feedback in relation to the virtual mine in which participants were situated. This was further supplemented via the provision of graphical icons and auditory cues in order to inform participants as to their status during interaction.

The following sections detail the data analysis for feedback as a means of determining the efficacy of this Problem-based Learning Design Principle within FUMES. This was undertaken according to evaluation criteria established from the literature (Table 2.16) pertaining to the perception and understanding of feedback, the modification of user behaviour due to feedback, the relevance of feedback, and the integration of feedback.

Perception and Understanding of Feedback

A series of four questionnaire prompts were employed using both Experienced Participants and Novice Participants in order to assess their perception of feedback within the simulation environment, particularly in relation to the personal radio construct which utilised auditory cues

in relation to participant interaction (Figs. 7.68 through 7.71).

The simulation provided me with feedback in response to my actions
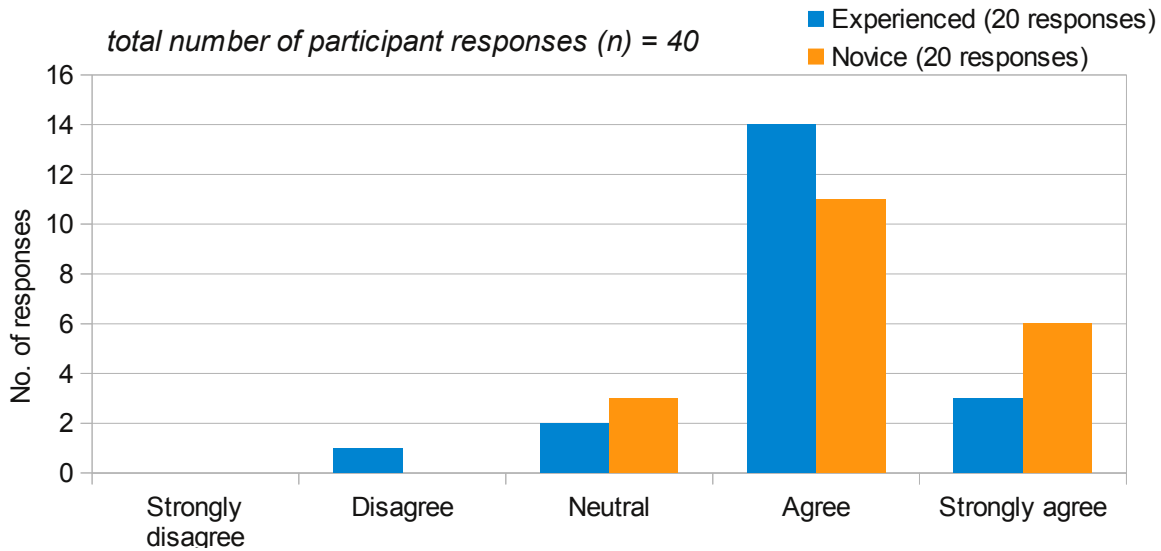
Figure 7.68. Extent to which participants recognised feedback in response to their actions

The walkie talkie kept me moving in the right direction within the 3D environment
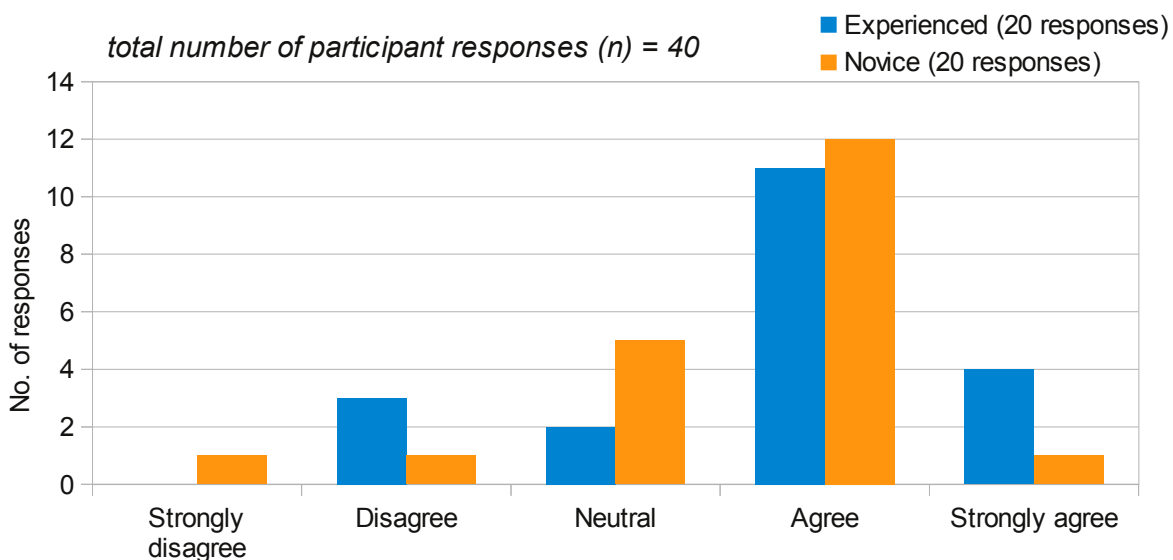
Figure 7.69. Extent to which feedback provided by the personal radio construct assisted them to keep moving in the right direction

The walkie talkie told me when I needed to use my self-rescuer within the 3D environment
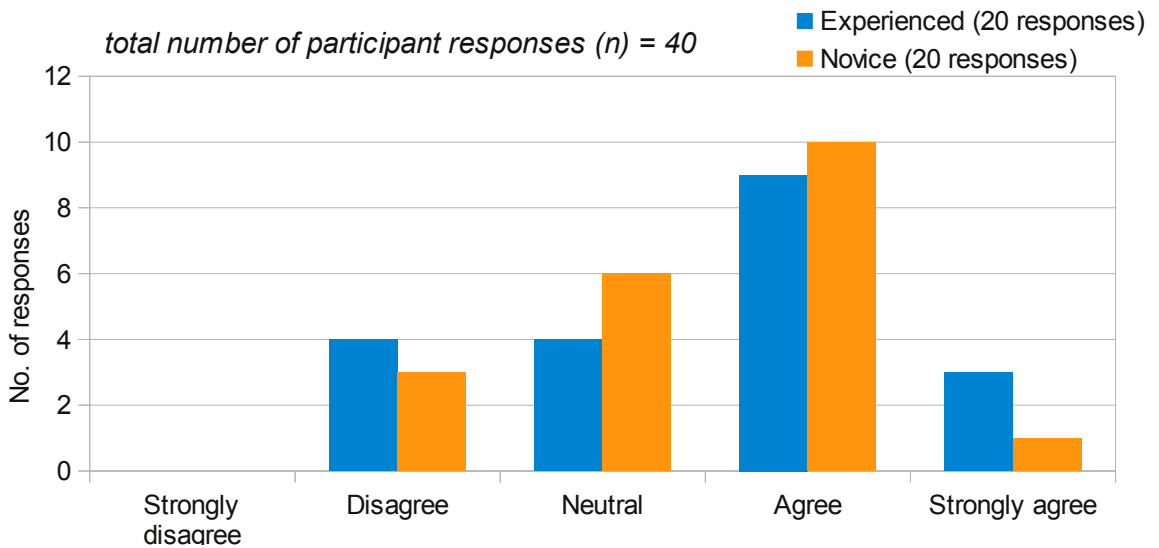
Figure 7.70. Extent to which feedback provided by the personal radio construct informed them when they needed to use their self-rescuer

The walkie talkie let me know when I was getting too close to a fire within the 3D environment
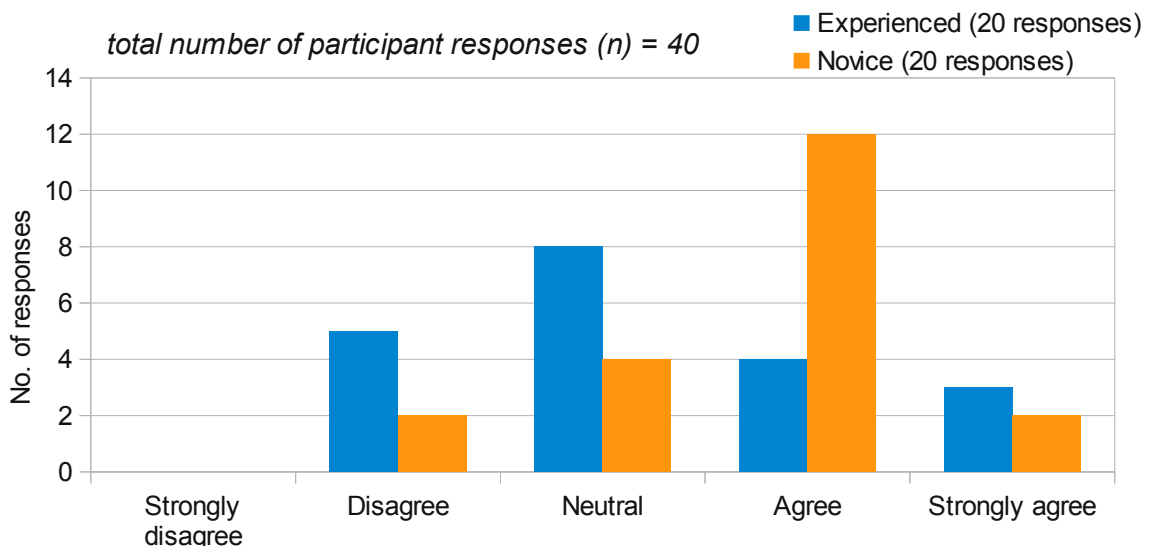
Figure 7.71. Extent to which feedback provided by the personal radio construct informed them when they were getting too close to a fire

Both Experienced Participants and Novice Participants acknowledged that the 3D simulation environment provided feedback in response to their actions (Fig. 7.68). While the feedback

provided by the personal radio was effective at keeping participants moving in the right direction (Fig. 7.69), it was not as effective at informing participants when they needed to use their self-rescuer (Fig 7.70). The feedback provided by the personal radio when in close proximity to a fire also resonated more effectively with Novice Participants than Experienced Participants (Fig. 7.71). However, a statement made by an Experienced Participant during interview suggests that the inconsistency of the self-rescuer and fire proximity feedback may have been due to participants not hearing the auditory feedback clearly or being unaware of it given their focus on the problem-solving task at hand:

- " ... because as you're walking along in that sort of scenario you don't always hear everything on the radio because there's so much going on around you and you may miss things on the radio."

Interview responses elicited from four Experienced Participants and three Novice Participants further suggest that the feedback provided by the personal radio was shaping their behaviour within the simulation environment. Participants recognised a relationship between their actions and the auditory cues provided, with a number of responses highlighting the impact of auditory cues which questioned their behaviour:

- "If you were going totally the wrong way and just wasting your time, it was quite happy to tell you that and constantly going 'are you sure you're going the best way' I think it said. It was constantly asking you the question, 'are you going the right way, are you doing this the most efficient way?'";
- " … it warned me if I walked near smoke or walked up the escape way.";
- "If I was going the wrong way it would say I was going the wrong way, turn around.", and;
- "I was climbing up the ladder and it said 'Did you really need to climb up there?'"

Further comments made during interview demonstrated that the feedback that was provided by the simulation environment was immediate and perceivable:

- "As soon as you got to a ladder, it would give you the option to press c to go up the ladder.", and;
- "When I was pressing keys, I was getting a response straight away. It did appear that as you were pressing keys you were actually moving and therefore you could respond."

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A number of statements made by participants during interview also emphasised the provision of feedback in relation to participants' proximity to smoke and physical exertion within the virtual mining environment:

- " … if you were close to smoke, you coughed.", and;
- "You could hear yourself coughing and breathing heavy if you were doing more physical exertion."

Collectively, the questionnaire and interview responses demonstrate that both Experienced Participants and Novice Participants acknowledged feedback from a number of sources. Auditory feedback provided by the personal radio was effective at informing participants that they were moving in the wrong direction, but less effective advising them when they were too close to a fire or when they needed to use their self-rescuer. However, this feedback may have gone unnoticed by some participants due to their focus on the problem-solving task and conflicting audio sources within the virtual mining environment. Comments elicited during interview indicate that participants associated their actions with the auditory feedback provided by the personal radio, with an emphasis on auditory cues questioning their actions and behaviour. Interview responses also suggested that feedback was provided immediately in response to participant interaction and demonstrated recognition of feedback in relation to proximity to smoke and physical exertion.

Modification of User Behaviour due to Feedback

The input logs which recorded interaction within the simulator were analysed for instances of feedback affecting participant behaviour. Twenty-six input logs were examined for occasions of participants changing their behaviour in response to feedback provided by the 3D simulation environment. Analysis was limited to instances where participants could be observed making obvious, immediate, and determined changes to their behaviour in direct response to feedback that was provided, as detailed in Table 7.1.

Table 7.1. Observable responses to feedback within the 3D simulation environment

Action	Feedback	Observable response to feedback
Participant heads in the wrong direction	Auditory cue asking the user if they are sure they are heading in the right direction	21 / 22 participants responded to the feedback by changing the direction in which they are moving

Participant continues to head in the wrong direction	Auditory cue that directly instructs the user to turn around as they are heading in the wrong direction	7 / 9 participants responded to the feedback by turning around and moving in the opposite direction
Participant encounters smoke	Visual depiction of smoke within the 3D simulation environment in addition to an auditory cue asking the user what they should do when they encounter smoke	9 / 11 participants responded to the feedback by equipping their self-rescuer
Participant enveloped in smoke	Visual depiction of smoke within the 3D simulation environment in addition to an auditory cue representing user coughing continually	2 / 5 participants responded to the feedback by retreating from the smoke filled area
Participant encounters fire	Visual depiction of fire within the 3D simulation environment in addition to an burning auditory cue	11 / 12 participants responded to the feedback by moving in a direction away from the fire
Participant attempts to run with self-rescuer equipped	On-screen text which informs the user that they can't run while they are using their self-rescuer	2 / 4 participants responded to the feedback by ceasing attempts to run
Participant gets too close to a vehicle fire	Auditory cue informing the user that they are getting too close to the fire	2 / 3 participants responded to the feedback by moving away from the fire
Participant navigation	Visual information provided by the 3D simulation environment	23 / 26 participants were observed to pause to examine spatial cues as they moved through the virtual mine
Participant orientation	Visual information provided by the 3D simulation environment	19 / 26 participants were observed to move their viewing perspective to examine the spatial cues around them within the virtual mine.

The input log data indicates that participant behaviour was modified as a result of feedback provided by the 3D simulation environment (Table 7.1). Participants were observed to make use of the visual feedback provided by the 3D simulation environment to facilitate orientation and navigation. The auditory feedback questioned the user when they moved in the wrong direction or directly instructed them to turn around when they continued to do so successfully, instigating changes in the user's heading. Feedback demonstrating the presence of smoke and fire prompted participants to avoid these hazards or equip their self-rescuer in order to negotiate them safely.

Relevance of Feedback

Questionnaire prompts were utilised to evaluate the relevancy of the feedback provided within

the 3D simulation environment using both Experienced Participants and Novice Participants (Figs. 7.72 and 7.73).

The simulation provided me with feedback that was relevant to my actions
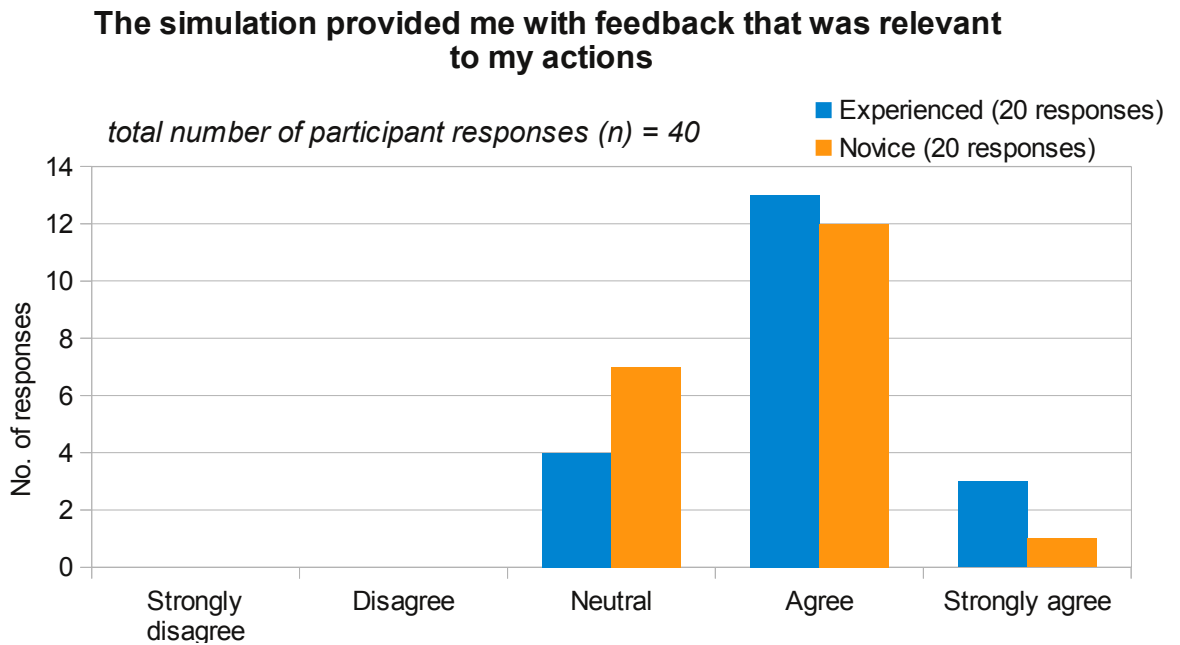
Figure 7.72. Extent to which feedback was relevant to participant action

The simulation provided me with feedback that was relevant to the training scenario
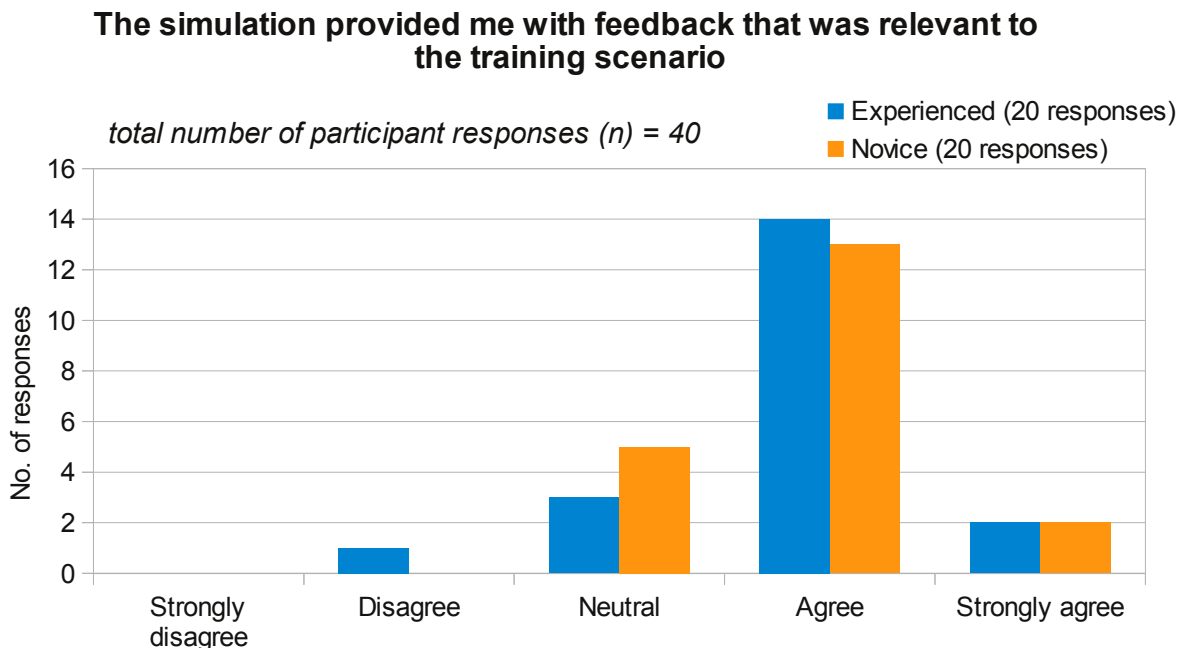
Figure 7.73. Extent to which feedback was relevant to the problem-solving task

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Experienced Participants and Novice Participants indicated that relevant feedback was provided in response to their actions (Fig. 7.72), and that the feedback that was provided was also relevant to the problem-solving task (Fig 7.73).

This was consistent with interview responses elicited from four Experienced Participants as to the suitability of feedback in relation to the real world mining environment. Comments provided by these Experienced Participants demonstrate that the provision of relevant feedback contributed to the authenticity of the 3D simulation environment in terms of the behaviour of key objects within the virtual mine:

- "I think what you're talking about was if I walked into smoke, did it get thicker and that sort of stuff? Yes, that was there … For this mine, it was appropriate.", and;
- "I think that it is critical because when they go from point A to point B they have to do it in the most efficient manner. Self-rescuers have got a finite length of life, and it's important that it is used wisely."

Additional comments emphasised the value of feedback that would not be provided during a real world emergency evacuation scenario in developing their understanding and awareness of the problem:

- "It was really good. It was probably better than the real world mine because you actually get feedback from something like that.";
- " Yeh, I think so, because you don't notice how quickly your heart rate increases … You don't realise how much energy you're using", and;
- "Yeh, I thought it was good that, because I thought I was walking towards the decline and I walking into some drive in the level, and I thought 'where am I', and it would say 'are you headed in the right direction', so that was good because you wouldn't be able to tell straight away underground that you weren't headed in the right direction"

The questionnaire and interview responses demonstrated that feedback was provided in response to participant interaction within the 3D simulation environment. This feedback was relevant to the problem-solving task at hand and also contributed to the authenticity of the virtual mining environment. Additional feedback in the form of the heart rate monitor and the auditory cues used to redirect movement in the event of misdirection, for example, served to highlight significant aspects of the problem and facilitate resolution in a manner that was not

available during the real world problem scenario.

Integration of Feedback

Four Experienced Participants and three Novice Participants were queried during interview in relation to how well the 3D simulation environment responded to their actions. The responses of participants from both groups indicate that feedback was effectively integrated into the simulation environment where immediate responses were provided to their actions in a manner that reflected real world activity:

- " ... it was good, and quick.";
- "Very well, pretty well instant. Whatever you did, it did.";
- "If I asked it to do something, it did it.", and;
- "Yeh, it was pretty good. Pretty realistic the way you move and everything."

However, a number of comments suggest that participants who were unfamiliar with the keyboard control scheme experienced some initial disassociation between their input and the feedback that was provided:

- "It took me a little while to get used to using the arrow keys and the keys the way that they were set up … You actually had to spend a few minutes familiarising and getting a feel for how to use the program and how to walk and that sort of thing.", and;
- "I used the arrow keys and that took a while to get used to but that is just me not being familiar with the keyboard."

This implies that while the 3D simulation environment provided feedback which afforded an immediate and realistic sense of interaction, the extent to which it was integrated into problem-solving activity was contingent on participants' familiarity with the control mechanisms.

Summary for Feedback

The technical capabilities of 3D simulation environments afford great flexibility when providing users with feedback in response to their performance in order to guide the problem-based learning process. FUMES was designed to provide feedback at both the facilitator and task

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environment level to guide participant attempts at resolving the problem in a manner that would appeal to their existing knowledge of the real world problem (Chapter 4.4.1).

Findings elicited from the FUMES implementation regarding the understanding of feedback, the modification of user behaviour due to feedback, the relevancy of feedback, and the integration of feedback demonstrated that participants were assisted in their attempts to achieve resolution and developed their understanding of the real world problem as a result of the feedback that was provided. Experience Participants and Novice Participants acknowledged that the 3D simulation environment provided immediate feedback in response to their actions and behaviour, some of which went unnoticed due to the simultaneous presentation of multiple forms of feedback and their preoccupation with the problem-solving task. Participants associated their actions with the auditory feedback provided by the personal radio, with an emphasis on those auditory cues that questioned their actions and behaviour. Further observations indicated that participants made extensive use of their ability to freely orientate their viewing perspective to obtain visual feedback from the virtual mining environment to maintain spatial awareness and facilitate effective navigation. The feedback that was provided was adjudged relevant to both participants' actions and the problem-solving task at hand and contributed to the authenticity of the virtual mine in terms of demonstrating the behaviour of objects that had a bearing on the problem-solving task, such as smoke and the oxygen supply of self-rescuers. Participants emphasised the value of feedback that was provided in addition to what would be available during a real world emergency evacuation, whereby the heart rate monitor and auditory cues used to redirect wayward movement served to highlight important aspects of the problem and facilitate resolution. Feedback was effectively integrated into the 3D simulation environment such that participants were afforded an immediate and realistic sense of interaction, although familiarity with the keyboard was necessary in order for participants to effectively associate their movement input with the visual feedback that was provided in response.

This suggests that the technical capabilities of the 3D simulation environment allowed for the provision of authentic and relevant feedback in immediate response to participant interaction such that a realistic representation of the real world problem was possible. While these technical capabilities allowed multiple forms of feedback to be provided simultaneously, the auditory feedback provided by the personal radio construct needed to be given higher priority so that it could be clearly acknowledged by participants. Observations of participant behaviour in response to feedback provided via the personal radio indicated that auditory cues phrased in the form of a question tended to be more effective at inducing behavioural change than those

phrased as a direct instruction. Further observations of participant behaviour demonstrated the value of being able to freely orientate the viewing perspective to maintain situational awareness and navigate effectively by using the immediate and dynamic visual feedback provided by the 3D environment. Participant responses to the smoke and self-rescuer feedback in terms of their contributions to authenticity suggest that aspects of the simulation which required high functional fidelity needed to provide perceivable feedback that demonstrated their behavioural characteristics. However, the ability of the personal radio auditory cues and graphical icons, such as the heart rate monitor, to promote participants' awareness and understanding of the real world problem suggest that the authenticity of the feedback that was provided could be sacrificed in the interests of guiding the learning process and developing knowledge.

This indicates the need to utilise the technical capabilities of 3D simulation environments to provide feedback that is consistent with the real world problem and appeals to users' existing contextually relevant knowledge, whilst also guiding their search for resolution. Analysis of the data collected during the FUMES implementation indicates the following findings in relation to the feedback Problem-based Learning Design Principle:

- Feedback which guides users towards problem resolution should be more prominent than feedback provided by the task environment. Such facilitatory feedback should be louder than background task environment noises, if auditory, or placed in a conspicuous and easily observable location, if visual. Multiple forms of feedback can be employed to convey the same message simultaneously in order to establish prominence. As an example, facilitatory feedback in the form of on-screen text could be situated in a central area of the screen, presented in a vibrant colour, or utilise a large font in order to ensure that it is noticed by the user;
- Where possible, feedback that is provided within a facilitatory capacity should question misguided or misdirected user behaviour, rather than providing direct instruction. This entails phrasing auditory or textual cues in the form of a question that prompts the user to examine their behaviour within the broader context of the problem-solving task;
- Users should be provided with the ability to freely orientate their viewing perspective so that they can make continued use of the immediate and dynamic visual feedback provided by the 3D environment. Appropriate control mechanisms for manipulating the viewing perspective should be allocated during the design process, such as a mouse or analogue stick on a game-pad or controller, where the user can freely orientate the viewing perspective at their discretion;

- Feedback should be used to instil functional fidelity within the 3D simulation environment. Visual or auditory cues should be employed to demonstrate the nature of key behaviour in a manner that appeals to users' knowledge of the problem domain. A problem-solving task requiring the user to correctly fit a fan belt to a motor could be expected to depict the tension in the belt and direction that it moved depending on the manner in which it was fitted, for example, and;

- The authenticity of the feedback that is provided during problem-solving can be ceded in the interests of developing the user's knowledge and guiding their attempts towards problem resolution. In practice, this means that additional visual or auditory feedback beyond that which may be appreciable during a corresponding real world problem scenario can be provided utilising the technical capabilities of 3D simulation environments. This could take the form of on-screen icons which detail the user's distance to the goal of the problem-solving task, for example.

7.3.2 Assessment

Assessment is employed within a problem-based learning environment to evaluate learners' ability to fulfil learning objectives whilst also assisting them in developing pertinent knowledge. Participants were assessed within the 3D simulation environment based on their ability to adhere to established emergency evacuation protocols used at Challenger using a combination of discrete metrics, such as outcome, time taken, and distance travelled, in addition to more complex, open-ended metrics, such as whether or not they took the ideal route to refuge (Chapter 4.4.2). Assessment feedback was provided at the conclusion of each problem-solving instance using simple text prompts.

The following sections detail the data analysis for assessment as a means of determining the efficacy of this Problem-based Learning Design Principle within FUMES. This was undertaken according to evaluation criteria established from the literature (Table 2.16) pertaining to the validity of assessment, fidelity of assessment, and integration of assessment.

Validity of Assessment

Given their familiarity with emergency evacuations in the Challenger mining environment, Experienced Participants and the Training Staff Member were interviewed as to whether

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FUMES fairly, accurately, and reliably assessed the outcome of each problem-solving instance. Responses from the four Experienced Participants who were interviewed suggest that the assessment feedback that was provided by the 3D simulation environment was consistent with participants' appraisal of their own performance and also reflect the extent to which they had followed correct procedure:

- "Definitely, which is good because you want to know you're doing things the right way.", and;
- "Yes. It gave you a pretty decent run down on what you'd done and whether you'd gone the right way or not. I think it was pretty fair. When smoke came along, it knew how long you had taken before you had smoke inhalation and all sorts of problems, so it was pretty good time wise."

However, comments from the Training Staff Member indicated that some of the assessment feedback provided did not give an absolute account of what is was supposed to measure. The Training Staff Member made specific mention of the assessment measure that detailed whether or not the user took the ideal route to a refuge chamber in this regard, indicating that a binary response did not accurately reflect the open-ended nature of the activity. Further exposition indicated that the Training Staff Member was required to explain to participants that it was possible for there to be more than one ideal route to a refuge chamber which the assessment measure did not account for. Additional comments suggest that this discrepancy had the capacity to affect participants' approach to problem-solving activity, particularly for participants who were relatively inexperienced:

- "There were some … that were pretty open ended that you could possibly had three or four different outcomes for … some ... are to a certain extent, open to interpretation, so there's no right way or wrong way, there could be two or three different outcomes for that one particular scenario.", and;
- "Especially with new guys and guys who haven't done it in a while, if you've got old guys, it's not too bad because they can sort of say, well this, this, this, this, and they'll come back and say '*hey, this thing is telling me that I didn't do the right thing, hang on, there are three or four different scenarios that you could have had.*' So the guys were a little bit stand-offish with some of those, but once I explained to them, no, that's not exactly right, that's one possible outcome, you could have done this or this. So they were all right once they had it explained to them."

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Collectively, these responses indicate that while assessment measures were perceived as being consistent with participants' evaluation of their own performance, the evaluation of more open-ended metrics was more problematic. This was particularly evident for the assessment measure which detailed whether or not participants had taken an ideal route to a refuge chamber, which required the Training Staff Member to mediate in order to explain to participants that the feedback that was provided did not take into account the possibility of more than one ideal route for a given scenario.

Fidelity of Assessment

Four Experienced Participants and the Training Staff Member were queried during interview in relation to whether the simulation environment assessed the outcome of the problem-solving task in a manner that was accordant with real world measures. Responses demonstrate that participants were assessed using metrics that were similar to those used to gauge personnel performance during a real world emergency evacuation at Challenger:

- "I think that the assessment was fair within the way the program worked and it was looking at the right things.", and;
- "Definitely, yeah. What you've based FUMES on is what we base our emergency procedures on. What we do here is what you've been able to mimic in the program."

Additional comments elicited from Experienced Participants indicate that the assessment feedback allowed participants to learn from their mistakes when they deviated from established evacuation protocol:

- " … in a real world evacuation, once you're evacuated your shift boss and people like that will probably sit down and say *why did you go about it this way?* So it's good in the end to have the feedback to say this probably wasn't the best way to do it, because in real life, they'll want to know why you didn't do things exactly to procedure.", and;
- "I think what I learnt that I should of done was stop, put the self-rescuer on to start with, like put the self-rescuer on and stay where I was, and then walked."

Collectively, these interview responses demonstrate that the mechanisms for assessment employed within FUMES were consistent with the measures used to evaluate performance of

the real world problem. Participants tailored their behaviour in response to the assessment feedback that was provided at the end of each problem-solving instance where they were able to develop their understanding of real world emergency evacuation protocol used at Challenger.

Integration of Assessment

Interview responses were elicited from four Experienced Participants and three Novice Participants as to how well assessment measures were integrated within the 3D simulation environment in terms of evaluating participants' performance. Responses indicated that assessment was effectively integrated into the 3D simulation environment when participants were provided with a useful appraisal of their performance after the completion of each problem-solving instance:

- " … it gave you a breakdown of the whole scenario, which was good.";
- "Yes, feedback after scenario, best route etc., that was good.", and;
- "The feedback that we got, that said you took how long to get to where you're going, that was useful and I think appropriate too for what I'd actually done."

Additional interview comments demonstrated the value of assessment in providing an accurate evaluation of aspects of participant performance that they may not have appraised correctly, or that may not have been possible to measure during a real world problem scenario:

- " … when you are in that situation you didn't feel like things happened as quickly as they did. But when you sit down and go through it all, and you realise that you can relate it back to what it would have taken to do it."
- Whereas, if something like that happens, you don't really get any feedback because nobody knows. By the time you get your stench gas, it's only you that knows your record of how long it takes to get to a refuge chamber. It's actually good that you have something like that as you have an indication of roughly what I need to do it in, to get to a safe area in.

This demonstrates the value of the technical capabilities of 3D simulation environments, whereby assessment measures could be effectively integrated into the learning process to provide a detailed evaluation of participant performance.

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Summary for Assessment

Assessment can be integrated into 3D simulation environments to evaluate the user's ability to satisfy learning objectives and develop new knowledge within a problem-based learning pedagogy. The assessment mechanisms within FUMES were designed to evaluate participants' ability to adhere to emergency evacuation protocol at Challenger using a combination of discrete and open-ended metrics that were presented via a simple textual display at the conclusion of each problem-solving instance (Chapter 4.4.2).

Findings elicited from the FUMES implementation in relation to the validity, fidelity, and integration of assessment demonstrated that the technical capabilities of the 3D simulation environment provided an adequate means of monitoring participant performance. The assessment mechanisms employed were deemed to have provided a valid appraisal of participants' behaviour during problem-solving activity, although providing an accurate evaluation of more complex participant behaviour, such as whether or not they had taken an ideal path to refuge, proved difficult. Experienced Participants and the Training Staff Member indicated that the way in which participant performance was assessed within FUMES was consistent with measures used to evaluate performance after an emergency evacuation of the Challenger mine, which allowed them to learn from their mistakes when they deviated from established evacuation protocol. The technical capabilities of the 3D simulation environment allowed feedback to be effectively integrated into the learning process such that participants were provided with a detailed evaluation of their performance using metrics that may not have been feasible or practical to measure accurately during a real world evacuation.

This suggests that the assessment mechanisms integrated into FUMES provided an accurate and detailed appraisal of participant performance in a manner that allowed them to develop their understanding of emergency evacuation protocol at Challenger. However, the inability to accurately assess the suitability of the route that participants took to refuge demonstrated the need for more sophisticated methods of appraisal for complex or open-ended metrics. This was consistent with previous analysis which acknowledged that the means for evaluating participants' route to refuge was overly simplistic and did not properly take into account all possible permutations (Chapter 6.1.1). In contrast, the remaining assessment mechanisms effectively gauged performance in a manner that was consistent with real world measures such that participants could learn from their experience if they deviated from established evacuation protocol. This was made available via the technical capabilities of 3D simulation environments,

which allowed for every aspect of participant performance to be tracked and responded to during assessment in a manner that exceeded what is possible during a real world problem scenario.

This indicates the need to utilise the technical capabilities of 3D simulation environments to assess performance in relation to real world problem outcomes in order to appeal to existing knowledge of the problem domain and facilitate the transfer of learning. Analysis of the data collected during the FUMES implementation indicates the following findings in relation to the assessment Problem-based Learning Design Principle:

- Assessment metrics should reflect those used to evaluate the outcome of the real world problem in order to accommodate existing knowledge and the transfer of learning. In practice, this means that users should be assessed in relation to their adherence to real world solution methods and provided with meaningful feedback which corresponds to their performance, and;

- Assessment needs to accommodate multiple real world solutions, some of which may not be able to be evaluated adequately within the 3D simulation. Assessment mechanisms utilised to evaluate complex or open-ended user behaviour need to be sophisticated enough to accommodate all necessary possibilities and permutations in order to provide meaningful insight that users can learn from. Complex multivariate analysis, peer or instructor discussion, or real world assessment can be used in place of integrated assessment under these circumstances.

7.3.3 Information

Information is provided within a problem-based learning environment to augment learners' study and address the learning requirements of the problem. FUMES was designed such that participants were largely responsible for the acquisition of their own information by virtue of their interaction within the virtual mining environment (Chapter 4.4.3). Participants could freely move around the virtual mine and manipulate their viewing perspective in order to acquire spatial information and assess environmental conditions which could impact on their ability to reach refuge. As a concession to Novice Participants' lack of familiarity with the Challenger mining environment, these participants were also provided with a Mine Layout Diagram, depicting a two-dimensional cross section of the mine, detailing the depth of each level as well as the locations of refuge chambers and escape rises (Chapter 3.3).

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The following sections detail the data analysis for information as a means of determining the efficacy of this Problem-based Learning Design Principle within FUMES. This was undertaken according to evaluation criteria established from the literature (Table 2.16) pertaining to the extent of information available, integration of information, and application of information.

Extent of Information Available

Experienced Participants and Novice Participants were queried via questionnaire in relation to the use of the virtual mining environment as a learning resource during problem-solving activity (Fig. 7.74).

The mining environment provided information that I used to complete the training scenarios
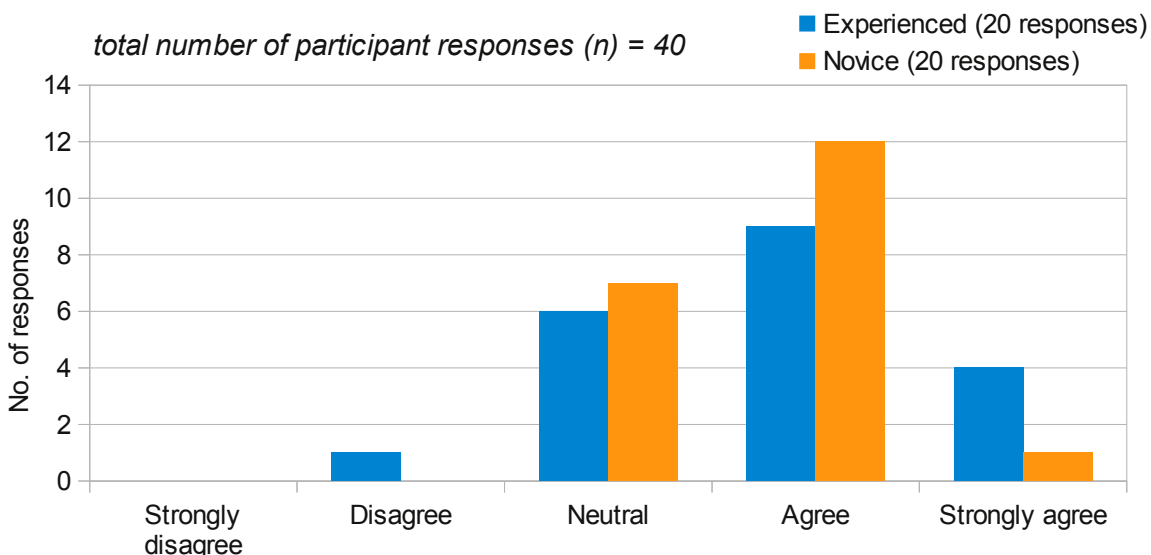
Figure 7.74. Extent to which the mining environment was an information resource

Participants from both groups used information provided by the virtual mining environment to complete the problem-solving task (Fig. 7.74). Experienced Participants, who were familiar with the Challenger mining environment, elicited spatial information from the virtual mine to maintain their bearings and determine a route to refuge. This was evidenced in the interview responses of four Experienced Participants when asked to identify the information they used to complete the problem-solving task:

- " ...straight away looking around to move out of the drive and into the decline";

- " … you've got a certain amount of time to really work out where you are and get your bearings and that, so it was good like that because you could actually see where you were and which is up and down. You actually had a really good perception.", and;
- " move to a refuge chamber, try not to go anywhere near smoke or obstruction, go an opposite way … and stick to the decline."

However, amongst Experienced Participants who where interviewed, the participant with the least amount of experience at Challenger indicated the need for additional learning resources beyond those provided by the virtual mining environment. This participant, who had only six months experience at Challenger, stated that they had to use the Mine Layout Diagram as a supplementary learning resource in order to orientate themselves and navigate the virtual mine:

- "I ended up getting a schematic of where the refuge chambers were. Once I got that, I was all good. Well, I was partially good, because I was still trying to figure out where I was. But once I knew where the refuge chambers were, I was all right."

This was consistent with interview responses provided by three Novice Participants which described their use of the Mine Layout Diagram in conjunction with spatial information elicited from the virtual mining environment:

- "I had the cross section of the mine diagram on a piece of paper which showed where everything was, so I knew if I was on level 760 I could go up to the next refuge chamber or down or whatever", and;
- "If you had a map in front of you and you'd been told that the refuge chamber at the 840 and the 740, you knew you had to go up because you were at the 820 and you had to go up to 840 because you knew that is where the closest refuge chamber was."

Collectively, the questionnaire and interview responses demonstrate that the virtual mining environment functioned as a source of information for both Experienced Participants and Novice Participants. Experienced Participants utilised spatial information elicited from the virtual mine to orient themselves and determine their route to refuge. Novice Participants did likewise, but utilised this information in association with a supplementary learning resource in the form of the Mine Layout Diagram. The Experienced Participant with the least amount of time at Challenger amongst those interviewed also utilised the Mine Layout Diagram in this regard . This indicates that the virtual mining environment served as an adequate source of

information where participants who were familiar with the Challenger mine could extract spatial information to orientate themselves and navigate. However, participants who lacked the necessary familiarity with the Challenger mining environment required supplementary resources in the form of the Mine Layout Diagram to assist them during orientation and navigation.

Integration of Information

Interview prompts were used to gauge the extent that participants felt information was integrated into the 3D simulation environment and whether it was sufficient to complete the problem-solving task. Responses provided by the four Experienced Participants interviewed suggest that they recognised the virtual mining environment as an adequate information resource from which they had to elicit information in order to effectively undertake problem-solving activity:

- "Yes, I knew what level I was at and I knew whether, well we know ourselves where the refuge chambers are, and it was telling us where there was smoke, or if there was just smoke in general, or where there was an obstruction. So, you know, you have to take a bit of responsibility for which way you're going to go. "
- "Yes, some of the scenarios I found that you got more information; a couple of them didn't give you as much information. I think they did that because it made you try to work out, because sometimes when you are working down there and it is pretty similar. If you're working in one area and then you go to work in a different area that you don't usually work in, you're not familiar with that area and sometimes you forget what levels you're on. It sort of made you think about where you were going and what you were doing, so it was good in that aspect."

In contrast, responses provided during interview by three Novice Participants suggests that they were not able to utilise the virtual mining environment as an information resource with the same degree of effectiveness as Experienced Participants:

- "I'm new to the mine site and I got lost. I knew where the escape ladder ways were, but I didn't know what level I was going to.", and;
- "In the smoke filled one, I felt like I was on my own. And it felt more like that the more frustrated I got. I eventually got to the fresh air base, but it was very frustrating,"

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These interview responses demonstrate that Experienced Participants were able to effectively make use of information they obtained within the virtual mining environment to maintain situational awareness and determine their course of action for evacuation. In doing so, Experienced Participants were prompted to consider what they were doing and relate it to real world application. In contrast, Novice Participants were less effective in their ability to utilise the information that was provided to orientate and navigate within the virtual mine.

This indicates that for Novice Participants, the combination of information provided by the virtual mining environment and the Mine Layout Diagram was insufficient for effective acquisition and application of spatial information. Novice Participants struggled to orientate themselves, which suggested that they encountered difficulty in collating these information sources to maintain awareness of their location and determine the path they needed to take through the mine to refuge. While Novice Participants could acquire information from spatial cues within the virtual mining environment, the Mine Layout Diagram provided no indication of their position in relation to these spatial cues.

Application of Information

Previous analysis of input log data (Chapter 7.3.1) established that participants utilised the virtual mining environment as a source of information during problem-solving activity. Participants were observed to adjust their viewing perspective in relation to spatial cues during the process of traversing the virtual mine to maintain locational awareness as they navigated towards a refuge chamber.

However, observations made by the Training Staff Member (Chapter 7.1.1) demonstrate that Novice Participants struggled to orientate and navigate within the virtual mining environment, such that the Training Staff Member was required to assist them:

- "The new guys who didn't know the mine and just got thrown straight into the program found it very, very hard."
- "I'd comfortably say near on 100% required my help. More so within the dead end areas where they had nothing to follow or lead them in the right direction. I either told them they needed to change direction – which was sometimes enough. Others I had to actually direct a fair way until they got back to the decline area. In relation to how many

would have made it to the chambers – it would have been very few would have made it."

Novice Participants were unable to effectively utilise the virtual mining environment and Mine Layout Diagram to orientate and navigate within the virtual mine. This was consistent with previous analysis which demonstrated that Novice Participants lacked the procedural domain knowledge required to utilise spatial information to navigate effectively within the mining environment (Chapter 7.1.2). However, the comments made by the Training Staff Member demonstrate that the virtual mining environment could have been a more effective provider of spatial information if spatial cues had been represented with greater fidelity. This reflects Experienced Participants' assessment of the fidelity of the 3D simulation environment, where they identified that the absence of contextual details in the representation of servicing infrastructure had a negative impact on orientation and navigation within the virtual mine (Chapter 6.1.2).

This implies that for Novice Participants, the virtual mining environment and the Mine Layout Diagram were not effective sources of information to assist in the acquisition of spatial information necessary for orientation and navigation within the virtual mine. This could be attributed to an absence of procedural domain knowledge, where Novice Participants were unable to utilise spatial information effectively to navigate within the virtual mining environment. This was further exacerbated by a lack of contextual detail in relation to the representation of servicing infrastructure within the virtual mine, which were key spatial cues utilised by personnel to navigate within the Challenger mining environment.

Summary for Information

Information can be integrated into the 3D simulation environment to accommodate the requirements of the problem-solving task and enhance learning in accordance with a problem-based learning pedagogy. FUMES was designed to provide information during participant interaction within the virtual mining environment, where information regarding spatial characteristics and environmental conditions within the mine could be acquired as participants moved and manipulated their viewing perspective (Chapter 4.4.3). Novice Participants were also provided with the Mine Layout Diagram as a supplementary learning resource in an attempt to address their lack of familiarity with the Challenger mining environment.

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Findings elicited from the FUMES implementation regarding the extent of information available, integration of information, and application of information indicate that the information that was provided was sufficient for Experienced Participants, but not Novice Participants. The virtual mining environment functioned as an adequate source of information for the elicitation of spatial information for participants who were familiar with the Challenger mining environment. As such, Experienced Participants were able to effectively utilise information that they acquired within the virtual mine to effect completion of the problem-solving task, and in doing so, were prompted to consider what they were doing and relate it to real world application. However, Novice Participants, who were relatively unfamiliar with the real world mining environment, needed to use the Mine Layout Diagram as a supplementary information resource to assist them during orientation and navigation. The combination of the Mine Layout Diagram and the virtual mining environment as sources of information proved ineffective, as Novice Participants encountered difficulty in correlating the acquired information to maintain awareness of their location and the path they needed to take through the mine to refuge. This was attributed to a deficiency in procedural domain knowledge, whereby Novice Participants did not know how to utilise the spatial information elicited from these resources to navigate effectively within the virtual mine. This was further compounded by a lack of contextual detail in the representation of key spatial cues, such as servicing infrastructure, which were used as navigational aides within the real world mine.

This suggests that the 3D simulation environment provided information that was consistent with the real world problem scenario. However, the application of this information was contingent on requisite domain knowledge. Experienced Participants were effectively able to assume responsibility for the acquisition of learning resources as they had the necessary experience within the real world mine to make use of the spatial information that was acquired to orientate and navigate. In comparison, Novice Participants were unfamiliar with the Challenger mine and required more learning resources to address this knowledge deficiency. However, they struggled to utilise the Mine Layout Diagram as a supplementary learning resource in conjunction with information elicited from the virtual mine, as the Mine Layout Diagram identified spatial cues within the mine, but not the user's position in relation to them. This suggests that the Mine Layout Diagram should have been integrated into the 3D simulation environment and amended to detail participants' position within the mine in order to address Novice Participants' lack of familiarity with the Challenger mining environment.

This indicates the need to utilise the technical capabilities of 3D simulation environments to

provide information which augments the user's existing knowledge of the problem domain to enable completion of the problem. Analysis of the data collected during the FUMES implementation indicates the following findings in relation to the information Problem-based Learning Design Principle:

- The 3D environment functions as a source of information by virtue of the visual and auditory cues that are provided dynamically as the viewing perspective is moved or orientated. This can be used to encourage users to take responsibility for the acquisition and application of information to encourage active decision making and the abstraction of knowledge during exploration and observation of the task environment;

- The provision of information should be closely aligned with users' knowledge of the problem domain as identified during situation analysis. During design, a flexible degree of information can be provided in order to address potential deficiencies in knowledge of the problem domain. For example, users could be provided with a button input which displayed a schematic diagram during a problem-solving task which required them to diagnose an electrical fault on a circuit board, and;

- Any information that is needed to undertake the problem-solving task should be integrated into the 3D simulation environment so that users can acquire, correlate, and utilise it effectively. In practice, this means taking advantage of the technical capabilities afforded by 3D simulation environments to provide multiple sources of information simultaneously. This information can be modified in response to user interaction or changes to problem characteristics, if necessary.

7.3.4 Learner Control

The learning process within a problem-based learning pedagogy can be can be tutor directed, partially learner and facilitator directed, or learner directed, with responsibility for determining the amount and sequence of information to be learned delegated accordingly. FUMES was designed so that control of the learning process was shared between the user and the simulation environment, whereby the user was responsible for their learning in relation to maintaining spatial and situational awareness, while the simulation environment dictated what was to be learned from the problem in terms of potential emergency evacuation scenarios in the Challenger mine (Chapter 4.4.4). The simulation environment also administered control over the learning process by virtue of a facilitator construct which was used to guide participants during problem-solving activity via a combination of prompts which provided direct instruction and

questioned their behaviour. These were presented via auditory cues under the guise of radio communications from a personal radio.

The following sections detail the data analysis for learner control as a means of determining the efficacy of this Problem-based Learning Design Principle within FUMES. This was undertaken according to evaluation criteria established from the literature (Table 2.16) pertaining to control of the learning process, integration of learner control, and suitability of learner control.

Control of the Learning Process

Two questionnaire prompts were employed to compare the perceptions of Experienced Participants and Novice Participants in relation to the extent to which they felt in control of the learning process, and the extent to which they felt the simulator was in control of the learning process (Figs. 7.75 and 7.76).
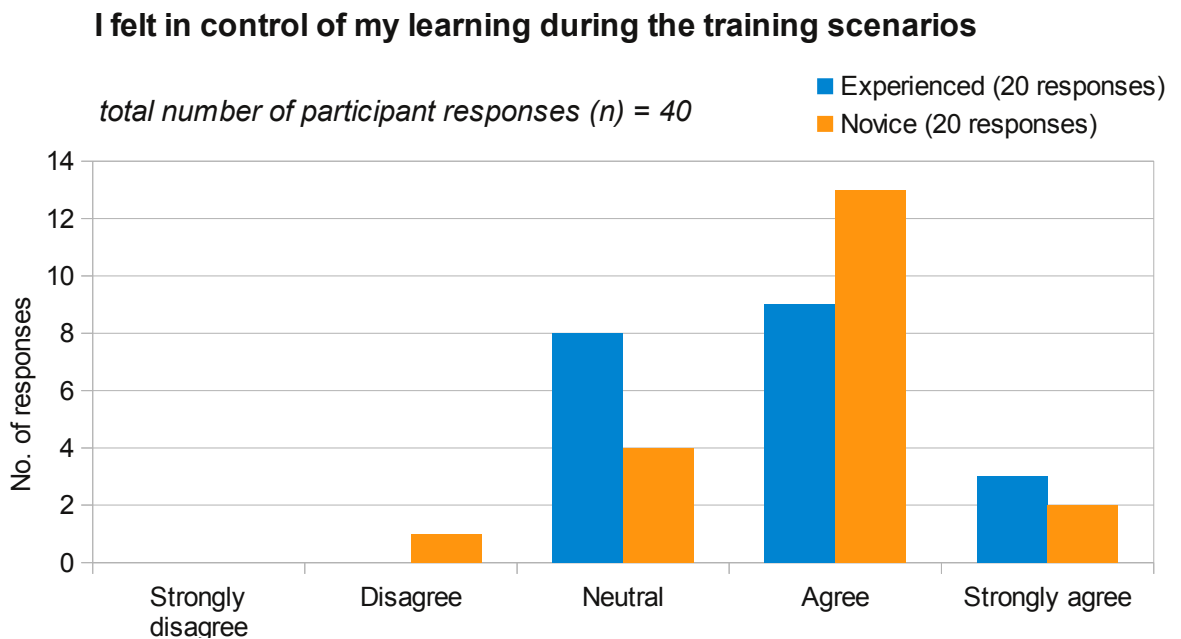
Figure 7.75. Extent to which participants felt in control of the learning process

The simulation controlled what I learned during the training scenarios

total number of participant responses (n) = 40
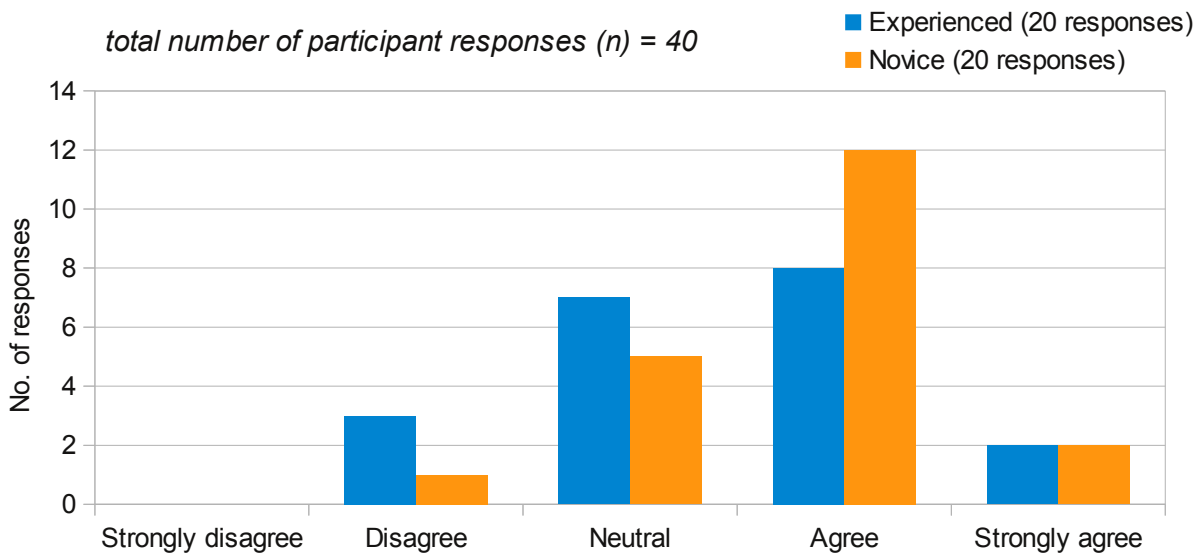
Figure 7.76. Extent to which participants felt that the simulation environment controlled the learning process

Participants from both groups perceived the learning process to be controlled conjointly by themselves and the simulation environment (Figs. 7.75 and 7.76). The responses provided by Novice Participants suggests that the distribution of control was relatively equitable in this regard, where as Experienced Participants indicated that they felt that they exerted more control over the learning process than the simulation environment.

Interview responses elicited from four Experienced Participants and three Novice Participants were consistent in this regard, indicating that control of the learning process was shared between the user and the 3D simulation environment. Comments provided by Experienced Participants imply that they were reinforcing their existing knowledge by actively responding to the circumstances of the problem-solving task dictated by the 3D simulation environment:

- "I felt that the program was delivering the process, rather than me being in control of it, because I was responding to what the program was doing and what was expected of me.";
- "I think it was kind of in control a little bit of what kind of things you need to learn, which is good because if you've never seen the mine before, they're things you need to learn.";

- "A bit of both, definitely a bit of both, because there are certain things you do underground, but the simulator was prompting you to reinforce it. So you'd kind of be like ah, so that's why you do that and that could be a good use of this because you're actually carrying out the emergency situation ...", and;
- "... it was kind of prompting you to reinforce knowledge that you already have.";

Additional comments from Experienced Participants provide insight as to the manner in which they exercised control of the learning process. Their statements indicate that they were responsible for determining their location and formulating an approach for reaching a refuge chamber during problem-solving activity in FUMES:

- "You've got to take your own responsibility as to how you get to a refuge chamber, what path you take."
- "It was easy to get flustered when I didn't know where I was going. Forces you to actually walk around and figure out what is going on.", and;
- "It sort of felt like you're in control when you actually knew where you were going and you had a plan in your head. So you sort of felt in control then. Pretty straight forward once you worked out where you were heading and what sort of plan, were you going to take the decline and what is happening and that";

In contrast, the interview responses provided by Novice Participants suggested that they were taking an active role in the development of new knowledge, rather than reinforcing existing knowledge, by engaging with problem-solving activity that was established within the context of emergency evacuation procedures at Challenger:

- "They've got their emergency procedures in place, so you're learning them, but you're in control of what you do.";
- "I was learning it as I was going … ", and;
- " … you're always learning about it, but you were in control of what you were doing …";

Collectively, the questionnaire and interview data indicated that participants perceived the learning process to be controlled by both themselves and the simulation environment. While FUMES dictated the knowledge to be learned by specifying the circumstances of problem-solving activity, Experienced Participants exerted control over the learning process by taking

responsibility for maintaining situational awareness and formulating an approach for getting to refuge, which served to reinforce their existing knowledge. Conversely, Novice Participants were acquiring new knowledge, rather than reinforcing existing knowledge, as a result of active participation in problem-solving activity that was established within the context of emergency evacuations of the Challenger mine.

Integration of Learner Control

In order to gauge the extent to which control of the learning process was integrated into the 3D simulation environment, four Experienced Participants and three Novice Participants were queried during interview in relation to whether they were required to take responsibility for their own learning. Responses provided by both Experienced Participants and Novice Participants demonstrated that they were responsible for learning how to orientate themselves, maintain situational awareness, and determine a safe path to refuge during problem-solving activity:

- "I had to turn around and shine my lamp on the walls to figure out where you were and stuff like that. You had to figure that out by yourself, the signage and stuff."
- " … I can recall needing to figure out was whether I was going up or down while the voice was on the radio telling me that I wasn't going in the right direction.", and;
- "I kind of thought get out of the smoke, put your self-rescuer on and then I went into the level and used the escape way to go up to the refuge chamber rather than going through thick black smoke and trying to find my way up."

However, additional comments from Experienced Participants demonstrate that the variable characteristics of the problem-solving task, such as participants' initial location and proximity to refuge chambers, and the location and severity of hazards and obstacles, dictated what they learned about potential emergency evacuation scenarios in the Challenger mining environment:

- "I walked up the decline and there was smoke and I needed to get from one level up to the next level where there is a refuge chamber above the smoke, well I don't know if it was above the smoke, but there was smoke coming down.", and;
- "It plonks you somewhere in the mine and says, this is what is going on, deal with it. And then as you cruise around, you might find a vehicle fire, or you might not."

This infers that the 3D simulation environment was well suited to providing participants with

control of the learning process. Participants could freely manipulate their viewing perspective and position within the mine, whilst also being able to deploy their self-rescuer to safely negotiate smoke at their discretion. This allowed them to develop their understanding of locational and situational awareness in addition to determining a safe route through the mining environment in order to reach a refuge chamber during an emergency evacuation. The 3D simulation environment was equally adept at exposing participants to an assortment of potential emergency evacuation scenarios by varying participants' initial location and the obstacles and hazards that they needed to overcome to resolve each problem-solving instance.

Suitability of Learner Control

Previous analysis demonstrated a disparity between Experienced Participants and Novice Participants in relation to their ability to orientate and navigate effectively within the virtual mining environment (Chapter 7.1.1). While Experienced Participants had no problems in this regard owing to their familiarity with the Challenger mining environment, Novice Participants struggled in comparison due to an absence of knowledge regarding the use of spatial characteristics for orientation and navigation (Chapter 7.1.2).

This suggested that Novice Participants may have benefited from additional support from the facilitator construct in terms of providing guidance when they became disorientated or lost within the virtual mine. While the facilitator construct did respond with auditory cues in the event that the user moved into sections of the virtual mine which were far removed from the path to a refuge chamber (Chapter 7.3.1), it lacked the functionality to recognise when the user was disorientated or unsure of how to navigate effectively. During the FUMES implementation, the Training Staff Member acted in a similar capacity to redirect Novice Participants when they got lost so that they could reach a refuge chamber and resolve the problem-solving task.

Summary for Learner Control

3D simulation environments can be used to engage users in the learning process by providing them with a degree of control over the amount of information that they learn, and the order in which they learn it. FUMES was designed such that the user determined what they learned in relation to their actions within the virtual mining, while the simulation environment dictated the circumstances of the problem-solving task in terms of the severity of the obstacles and hazards that needed to be overcome (Chapter 4.4.4). A facilitator construct which was programmed to

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respond to user interaction was also used to guide the learning process via the provision of auditory cues which provided direct instruction and questioned behaviour.

Findings elicited from the FUMES implementation in relation to control of the learning process, integration of learner control, and suitability of learner control indicated that learning was effectively directed towards the development of knowledge for emergency evacuations in the Challenger mine. Both Experienced Participants and Novice Participants acknowledged that the learning process was conjointly controlled by themselves and the simulation environment. Experienced Participants responded to the specific circumstances of the emergency evacuation to reinforce existing knowledge, while with Novice Participants it assisted in the development of new knowledge. Participants were afforded the freedom to manipulate their position, viewing perspective, and self-rescuer, which allowed them to enhance their understanding of locational awareness, situational awareness, and determining a safe route to refuge. Conversely, participants' understanding and familiarity with potential emergency evacuation scenarios at Challenger was developed by varying their initial location and the obstacles and hazards that they needed to overcome during each problem-solving instance. However, Novice Participants required greater support from the facilitator construct to address deficiencies in their knowledge of the problem domain when they became lost or disorientated within the virtual mining environment.

This suggests that the technical capabilities of the 3D simulation environment afforded flexibility in distributing control of the learning process between the user and the simulation environment. Control of the learning process was effectively split between participants and the 3D simulation environment such that participants were free to use the methods of interaction available to them to overcome obstacles. The position and severity of the smoke and fire obstacles were varied by the simulation environment for each problem-solving instance to maintain a degree of uncertainty and expose participants to a multitude of potential emergency evacuation scenarios within the Challenger mining environment. While the facilitator construct did provide guidance during the learning process, it needed to be expanded upon to assist disorientated Novice Participants who lacked the necessary domain knowledge to orientate and navigate effectively within the virtual mine. This could have been accommodated via the technical capabilities of the 3D simulation environment, whereby instances of disorientation could have been detected and responded to by the facilitator construct in order to assist participants to orientate themselves and formulate a path to refuge.

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This indicates the need to utilise the technical capabilities of 3D simulation environments to distribute control of the learning process such that users can enhance their understanding of the real world problem via active engagement in the problem-solving task. Analysis of the data collected during the FUMES implementation indicates the following findings in relation to the learner control Problem-based Learning Design Principle:

- The 3D simulation environment should assume greater control of the learning process when users' knowledge of the problem domain is insufficient to allow them to resolve the problem-solving task without assistance. Under such circumstances, the 3D simulation environment would assume greater responsibility for structuring the learning process via the utilisation of explicit cues or directives to guide the user towards resolution;
- Users should be free to utilise the methods of interaction that are available to them within the 3D simulation environment such that they can direct their own learning and develop or enhance their knowledge of the problem domain via active participation in problem-solving activity. This means that no restrictions or limitations should be placed on the user's methods of interaction unless dictated by the specific circumstances of the problem-solving task;
- The technical capabilities of 3D simulation environments should be used to vary or randomise the obstacles to resolution in order to expose users to a multitude of variations of the problem-solving task. The 3D simulation environment can be used to control what users learn about the real world problem in terms of the potential circumstances or scenarios which could be encountered, and in doing so, enhance real world application of the knowledge that is acquired, and;
- The technical capabilities of 3D simulation environments should be utilised to provide a facilitator construct which is capable of providing support in response to foreseeable deficiencies in the user's knowledge of the problem domain. During design, this entails analysing user behaviour and identifying instances where such deficiencies are manifest so that appropriate guidance can be provided to support the learning process and allow competition of the problem-solving task.

7.3.5 Reflection

Reflection is incorporated within problem-based learning environments to assist learners to

relate their new knowledge to their understanding, mindfully abstract their knowledge, and understand how their learning and problem-solving strategies can be applied to future problem-solving activity. FUMES was designed such that reflective prompts were incorporated throughout the learning process (Chapter 4.4.5). The facilitator construct issued reflective prompts using auditory cues which questioned the user's behaviour in the event that they used an escape rise or were traversing the mining environment in the wrong direction. On-screen text was also used at the conclusion of each problem-solving instance to present participants with a series of questions which challenged their understanding of the problem domain. These were tailored in response to the outcome of each problem-solving instance.

The following sections detail the data analysis for reflection as a means of determining the efficacy of this Problem-based Learning Design Principle within FUMES. This was undertaken according to evaluation criteria established from the literature (Table 2.16) pertaining to the identification and development of new knowledge, future applications of new knowledge, and integration of reflection.

Identification and Development of New Knowledge

Four Experienced Participants and three Novice Participants were queried during interview in relation to the new knowledge that they acquired as a result of using the simulation. Responses provided by Novice Participants indicated that FUMES served to instil a greater appreciation for maintaining locational awareness and knowing where refuge chambers were located during an emergency evacuation:

- "Make sure you look for signage so you know where you're going and things like that. Make sure you know where refuge chambers are and stuff are. I didn't know much about that stuff before", and;
- " Pay attention more about where refuge chambers are, even when I'm going down there in terms of subconsciously or consciously and then just keep a note of where they are just a little bit more closely then I did in the past that's all."

Responses provided by Experienced Participants indicated that they enhanced their understanding of the Challenger mining environment and the potential emergency evacuation scenarios that they could encounter in the event of a fire underground:

- "Yes, I definitely realised that all the escape ways were internal. Most other places I've worked at, the escape ways are on the decline";
- "I have acquired new knowledge because as I said I would have gone up that escape way around the fire to the refuge chamber that was one level above me, where as it's probably a better idea to do a bit more travelling and go a few levels below me to a refuge chamber", and;
- "It does give you a bit more knowledge in what can actually happen in that sort of environment. We've never had a fire here underground, so it gives you a bit of an insight into what it's like there. So it gives you a bit of knowledge, if there is a fire, that is the sort of environment you're going to be put in."

The same participants were asked to identify the aspects of problem-solving activity which they felt contributed to the development or enhancement of their knowledge. Responses provided by participants from both groups emphasised the experiential nature of problem-solving activity in this regard:

- "Knowing where to look on the walls for the signs and the flashing lights for the refuge chambers. Looking for smoke and things like that";
- "It put you in a scenario where you had to make the decisions", and;
- "It gives you the realistic times and the feedback at the end, that's good to know because if it happens in levels then you know roughly how long it's going to take … "

Collectively, the interview responses demonstrated that both Experienced Participants and Novice Participants could identify knowledge that they had developed during problem-solving activity in FUMES. Novice Participants developed their understanding of the significance of locational awareness and refuge chamber locations during an emergency evacuation, while Experienced Participants enhanced their understanding of the potential emergency evacuation scenarios that they could encounter in the event of an underground fire in the real world mine. The experiential nature of problem-solving activity was identified as key to the development of this knowledge, whereby participants could make decisions, observe the outcomes, and reflect on their understanding of emergency evacuation scenarios at Challenger.

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Future Applications of New Knowledge

Interview responses were elicited from four Experienced Participants and three Novice Participants in relation to the future applications of knowledge acquired during problem-solving activity. The feedback provided by participants indicated the procurement of knowledge that was transferable to the real world problem as a result of problem-solving activity being situated in a similar activity and context:

- " … it's a good refresher, so I don't think it gave me particularly new information. But it's worthwhile doing these simulations to keep things fresh in your mind.";
- " … it helps you understand more about the mine and what to do in an evacuation.", and;
- "Yeh, it would be, just being aware of how long things take. When you put a rescuer on, you don't think of how long it takes. When you're walking to somewhere and when you're trying to find an escape way or get out through the decline, you don't actually realise how long it actually takes you. But, when you see it in black and white like that you realise that if you didn't do something it might have saved you thirty seconds here, or a minute here, and that could be all the difference."

These comments demonstrated that little abstraction was required on the behalf of participants to recognise the future applications of the knowledge that they acquired to emergency evacuation scenarios at Challenger. This suggested that the authenticity of the 3D simulation environment allowed participants to readily reflect upon their learning and envision its real world application.

Integration of Reflection

Ascertaining the extent to which opportunities and support for reflection were integrated into the 3D simulation environment entailed the application of two questionnaire prompts using both Experienced Participants and Novice Participants (Figs. 7.77 and 7.78).

**I was given an opportunity to think about what I had done
after each training scenario**

total number of participant responses (n) = 40

■ Experienced (20 responses)
■ Novice (20 responses)
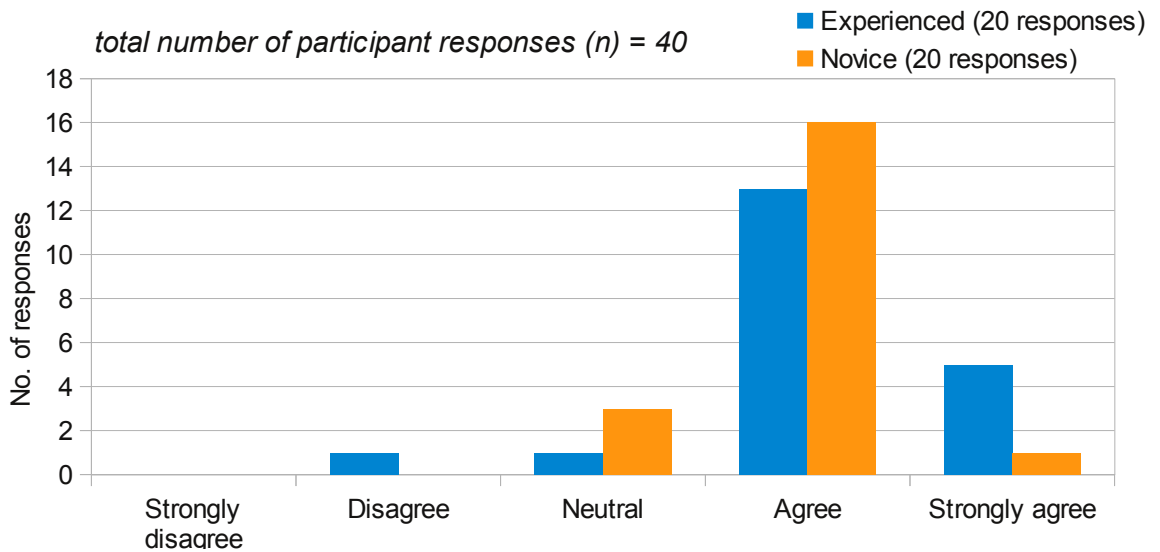
Figure 7.77. Extent to which opportunities for reflection were afforded after each problem-solving instance

**The simulation prompted me to think about specific things that
I did during each training scenario**

total number of participant responses (n) = 40

■ Experienced (20 responses)
■ Novice (20 responses)
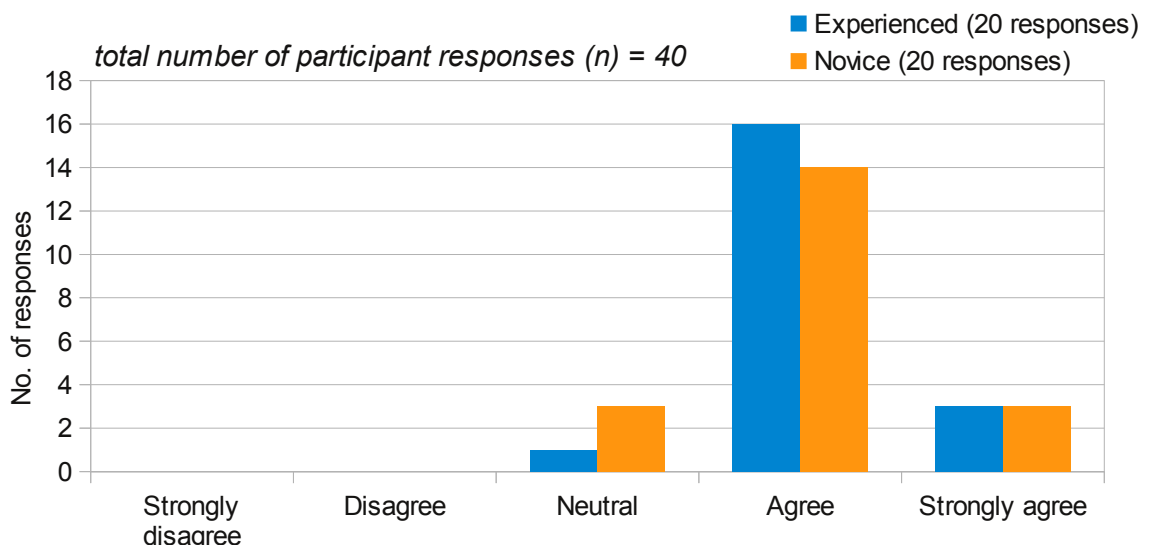
Figure 7.78. Extent to which the simulation prompted reflection during problem-solving activity

The simulation environment prompted Experienced Participants and Novice Participants to

reflect on their their actions during problem-solving activity (Fig. 7.78) and also provided opportunities for reflection at the conclusion of each problem-solving instance (Fig. 7.77).

Interview responses were elicited from four Experienced Participants and three Novice Participants
in order to obtain greater insight into prompts for reflective thinking within the simulation environment. Comments provided by Experienced Participants suggest that they reflected on their interaction during the course of relating their existing real world experience to the problem-solving task at hand. Their responses further suggested that this was an intuitive process undertaken of their own volition:

- "I've been dusted out a few times, it's not smoke, but it might have been a rock fall in the stope or something like that, that all of a sudden you get the dust is really thick and you need to move along or get out of there. A couple of times I've had my cap-lamp go flat, things like that. So it kind of makes me think about what you need to be doing in the situation."
- "It gets you to do that anyway, whether it prompts you or not, there's no official prompting, but just by putting you in that situation and saying get out of it, it does call on experiences you might have in what you might call self preservation."
- "The program didn't really prompt me to think like that, I sort of think that way anyway. At one stage there, I wasn't sure whether I was going to take the decline or the escape way, but then it asked me after I used the escape way do you think you made the right decision in using the escape way? It didn't prompt me before-hand"

In contrast, the interview responses provided by Novice Participants emphasised the reflective question prompts employed at the conclusion of each problem-solving instance in stimulating reflective thinking:

- "After each simulation a screen would come up and gave you a chance to realise what you'd done wrong and what you'd done right.", and;
- " … yep at the end of each scenario. How did that go? How did I screw that up?"

Both Experienced Participants and Novice Participants were thus encouraged to reflect on their performance within the simulation environment as they undertook and completed problem-solving activity. Experienced Participants were prompted to reflect on their actions within the

simulation environment during the process of relating their existing problem-solving experience to the problem-solving task at hand. In contrast, Novice Participants engaged in reflective thinking when presented with the reflective question prompts at the conclusion of each problem-solving instance. This suggested that opportunities and support for reflective thinking for both Experienced Participants and Novice Participants were effectively integrated into the 3D simulation environment.

Summary for Reflection

Reflection is employed within problem-based learning environments as a mechanism for developing understanding as to how newly developed knowledge can be applied to future problem-solving activity. FUMES employed reflective prompts to challenger participants' understanding of the problem domain both during and after each problem-solving instance, with post instance reflection tailored to the outcome of problem-solving activity (Chapter 4.4.4).

Findings elicited from the FUMES implementation in relation to the identification and development of new knowledge, future applications of new knowledge, and integration of reflection demonstrated that participants engaged in reflective thinking practices which encouraged the abstraction and transfer of knowledge. Experienced Participants enhanced their understanding of potential emergency evacuation scenarios which could be encountered at Challenger, whilst Novice Participants gained greater insight into the significance of locational awareness and refuge chamber locations during an emergency. Interview comments suggested that participants were able to reflect on their understanding of emergency emergency evacuation scenarios at Challenger by virtue of the experiential nature of problem-solving activity in FUMES. The authenticity of the 3D simulation environment also prompted participants to reflect upon the relationship between problem-solving and learning such that they could readily abstract the knowledge that was developed and envision its real world application. Opportunities for reflection were deemed to have been effectively integrated into the 3D simulation environment, whereby Experienced Participants were prompted to reflect on their interaction as they utilised their existing real world experience during problem-solving activity, while Novice Participants were encouraged to reflect upon their experience when presented with reflective question prompts at the conclusion of each problem-solving instance.

This suggests that the technical capabilities of the 3D simulation environment were well suited to encouraging reflective thinking amongst participants. Both Experienced Participants and

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Novice Participants were encouraged to reflect on their knowledge of emergency evacuation scenarios at Challenger by virtue of the experiential nature of problem-solving activity, whereby they made decisions and observed outcomes in order to derive understanding. Similarly, the ability of the 3D simulation environment to authentically represent emergency evacuation scenarios at Challenger allowed participants to easily abstract the knowledge that they acquired and reflect on its real world application. As such, Experienced Participants were intuitively encouraged to reflect on their performance during the process of applying their existing real world knowledge towards problem resolution. In contrast, more overt prompts for reflective thinking were required for Novice Participants, as they lacked the knowledge of the real world problem domain exhibited by their experienced counterparts.

This indicates the need to utilise the technical capabilities of 3D simulation environments to prompt reflection in users both during, and after, problem-solving activity. Analysis of the data collected during the FUMES implementation indicates the following findings in relation to the reflection Problem-based Learning Design Principle:

- Experiential problem-solving activity can prompt reflective thinking in users. Users must be provided with the ability to make their own decisions, to which observable outcomes must be associated, in order to assist them to develop their understanding and envision the application of newly acquired knowledge. As an example, a chemistry focussed problem-solving task which allowed users to choose chemicals to mix and observe the results of the concoction could be used as a means to prompt reflection in relation to real world lab safety;
- The 3D simulation environment should represent the real world problem authentically in order to encourage users to reflect on the real world usage of the knowledge that they acquire. The objects, obstacles, environmental conditions, and physical and behavioural characteristics that require authentic representation should be identified during the design process so that the level of abstraction required on behalf of users to reflect on the real world application of their developed knowledge is minimised, and;
- Knowledge of the real world problem domain should be elicited in order to encourage reflective thinking. The problem-solving task should be situated within a context that is similar to the real world problem to encourage reflection implicitly as users utilise their knowledge of the problem domain towards resolution. In the event that the user's knowledge of the problem domain is identified as being deficient, more explicit prompts for reflective thinking should be employed using the technical capabilities

afforded by 3D simulation environments.

7.4 Summary of Findings for the SUPL Design Framework

FUMES was designed as an emergency evacuation training platform for mining personnel at the Challenger mine using the SUPL Design Framework. Data collected during the FUMES implementation was used to evaluate the efficacy of each design consideration identified in the SUPL Design Framework and identify guidelines for their implementation in order to address the second research question proposed by this study.

Analysis of the data indicated that FUMES adequately accommodated the Situational Analytical Factors identified in the SUPL Design Framework. The problem-solving task was established within the common context of emergency evacuations of the Challenger mine, and embodied cues and relationships that were familiar to participants based on their knowledge of the problem domain. However, Experienced Participants performed more effectively than Novice Participants as a result of greater knowledge and experience with real world emergency evacuations at Challenger, particularly in relation to their locational awareness and ability to navigate within the virtual mining environment. Deficiencies were also identified in relation to the representation of key spatial cues within the virtual mine which had an impact on participant performance.

The Situational Design Considerations embodied by the SUPL Design Framework were also delineated effectively within FUMES. The problem-solving task was characterised in accordance with the real world problem and represented in a manner that appealed to participants' existing knowledge of emergency evacuation scenarios at Challenger. However, owing to inadequate knowledge of the domain, the problem-solving task was too ill-structured for Novice Participants to complete without assistance, which indicated the need for greater scaffolding by virtue of the provision of additional information during the statement of the problem.

Findings elicited from the FUMES implementation further indicated that the Problem-based Learning Design Principles detailed within the SUPL Design Framework served to effectively guide the learning process. Participants developed strategies for real world problem resolution

via experiential activity within the 3D simulation environment, whereby they made decisions, observed the outcomes, and reinforced or enhanced their knowledge accordingly.

Analysis of data obtained during the FUMES implementation thus demonstrated that the SUPL Design Framework effectively supported the construction and transfer of knowledge in 3D, problem-based learning environments. Significant differences in the performance of Experienced Participants and Novice Participants highlighted the necessity of rigorous situation analysis and the need for a flexible degree of learner scaffolding within the 3D simulation environment. Findings were also identified for each design consideration in the SUPL design framework. These are explored in further detail in the following chapter.

8 Guidelines for Implementation

The previous chapter established the validity of the SUPL Design Framework via analysis of the data collected during the FUMES implementation. The efficacy of each design consideration in the SUPL Design Framework was ascertained, where findings were identified to guide their implementation. This chapter explores these findings with a view towards establishing generalised design guidelines which can be used to inform the development of 3D, problem-based learning environments in other contexts using the SUPL Design Framework.

To provide structured recommendations for the development of such learning environments, the findings established in the summary sections of the previous chapter (see dot points on pages 210, 215, 217, 224, 228, 238, 243, 253, 261, 274, 283, 292, 299, 302, 308, 319, 325, 332, 339, and 346) will be collated, synthesised, and generalised for design in other contexts. This process will be undertaken in accordance with Oliver and Herrington's (2001) framework for the design of technology-mediated learning settings. Oliver and Herrington's framework emphasises knowledge construction through the embodiment of three critical components: the selection of learning supports, the selection of learning tasks, and the selection of learning resources.

These form the basic building blocks of e-learning design and can be aligned with the user, problem-solving task, and 3D simulation environment components of the SUPL design framework. Within this context, learning supports relate to the existing problem-solving knowledge that users draw upon to resolve similar problems, learning tasks pertain to the problem-solving task which serves as an approximation of the real world problem, and learning resources concern the system provided by the 3D simulation environment for the user to extract and use information. Figure 8.1 details the alignment of the SUPL design framework in relation to learning supports, learning tasks, and learning resources, accordingly.
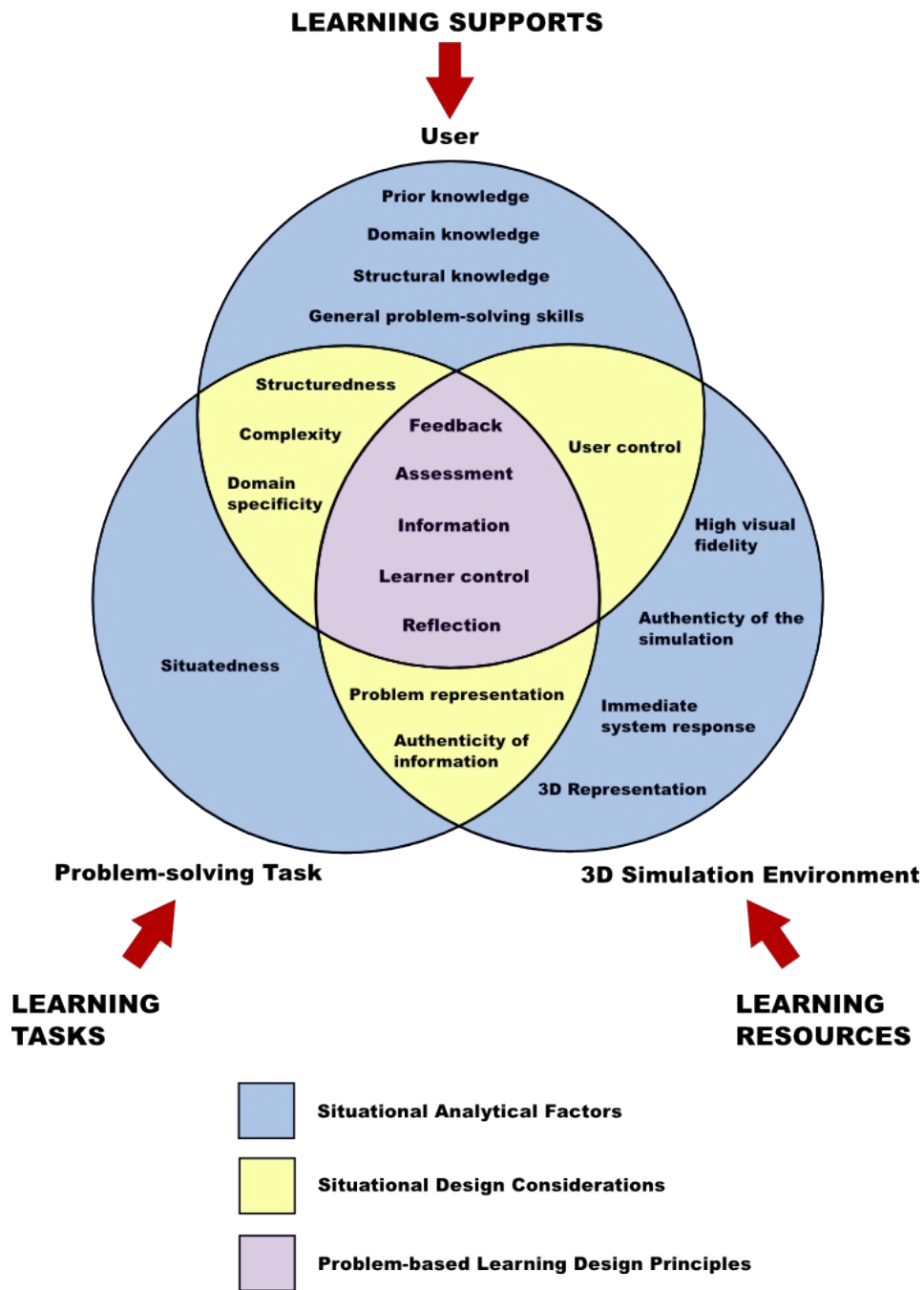
Figure 8.1. Alignment of the SUPL design framework with learning supports, learning tasks, and learning resources

Using the findings established in the previous chapter for implementing the design considerations in the SUPL Design framework, generalised design guidelines will be derived in alignment with learning supports, learning tasks, and learning resources (Fig. 8.1). This process is undertaken in the following sections:

- Chapter 8.1 develops generalised design guidelines for Situational Analytical Factors in the SUPL Design Framework;
- Chapter 8.2 formulates generalised design guidelines for Situational Design Considerations in the SUPL Design Framework, and;
- Chapter 8.3 elicits generalised design guidelines for Problem-based Learning Design Principles in the SUPL Design Framework.

The generalised guidelines presented in these sections will function as a design check-list for 3D, problem-based learning environments via the consideration of Situational Analytical Factors, Situational Design Considerations, and Problem-based Learning Design Principles. However, the interconnected nature of Situational Analytical Factors, Situational Design Considerations, and Problem-based Learning Design Principles in the SUPL Design Framework requires that balance issues be considered during the design process. This is discussed in Chapter 8.4 in terms of the need to make informed trade-offs and compromises between design considerations in order to develop a learning environment that best suits the needs of the user.

8.1 Guidelines for Situational Analytical Factors

Situational Analytical Factors encompass factors which exist outside the control of the designer that need to be accommodated to facilitate knowledge construction and learning transfer within a 3D problem-based learning environment. This includes the user's existing problem-solving knowledge which supports their learning, the situated aspects of the real world problem which comprise the learning task, as well as the technical capacity of the 3D simulation environment to provide learning resources which approximate real world problem-solving activity. These factors are identified during situation analysis of the real world problem and subsequently used to inform the design of the 3D simulation environment. Analysis of the data elicited during the FUMES implementation identified a series of guidelines relating to this process, which are detailed in Table 8.1 as follows:

Table 8.1. Guidelines for Situational Analytical Factors

	Guideline	Implementation example	Link to SUPL Design Framework
1	Identify the extent of users' familiarity with the problem domain and characterise it in terms	Clear differences in the performance of Novice Participants and Experienced Participants demonstrated the need for a detailed understanding of users'	Prior knowledge, domain knowledge, structural knowledge, and general problem-solving skills

	of prior knowledge, domain knowledge, structural knowledge, and general problem-solving skills.	existing knowledge of the problem domain to inform problem selection. The problem-solving task was found to be too ill-structured and complex for Novice Participants due to their inexperience with the real world problem. Experienced Participants encountered no such difficulties and were able to employ stronger, more effective strategies for resolution.	(Learning supports)
2	Determine the gap between users' knowledge of the problem domain and the knowledge needed to resolve the real world problem in order to identify areas in which the user may require support during the learning process.	During the FUMES implementation, Novice Participants required support to account for deficiencies in their knowledge of the problem domain. Induction training did not provide Novice Participants with the necessary knowledge of spatial characteristics and navigation within the Challenger mining environment which negatively impacted their performance within FUMES. Greater problem structure and more extensive information sources, such as an interactive map which detailed their position within the virtual mining environment, could have been used to provide better learning support for Novice Participants.	Prior knowledge, domain knowledge, structural knowledge, and general problem-solving skills (Learning supports)
3	Identify the knowledge needed to resolve the real world problem. The learning objectives for the simulation should be directed towards the development of this knowledge.	Personnel needed to understand the emergency evacuation procedure and be familiar with the Challenger mining environment in order to be able to evacuate safely during an emergency. The learning objectives for FUMES were thus focussed on developing participants understanding of the evacuation procedure and providing greater exposure to the Challenger mining environment.	Situatedness (Learning tasks)
4	Identify the environment in which the real world problem is situated, the circumstances and conditions under which problem-solving activity occurs, and the activities undertaken by problem-solvers as they engage with the problem.	The real world problem was situated within the Challenger mining environment during an underground fire, whereby personnel had to undertake evacuation procedures which required them to safely negotiate the mining environment to reach a refuge chamber. Experienced Participants performed more effectively than Novice Participants because problem-solving activity in FUMES was closely situated to the real world problem. This allowed Experienced Participants to make extensive use of their real world experience with emergency	Situatedness (Learning tasks)

		evacuations at Challenger, which Novice Participants lacked.	
5	Characterise the real world problem in terms of structuredness, complexity, and domain specificity.	The structuredness, complexity, and domain specificity of the problem-solving task in FUMES were modelled on the real world problem. Participants were able to immediately recognise the problem and were encouraged to utilise approaches to resolution which were consistent with their existing knowledge of emergency evacuations at Challenger.	Situatedness (Learning tasks)
6	Identify the actions, strategies, solution methods, and measures of success for resolving the real world problem.	Participants were successfully able to employ real world solution methods to resolve the problem-solving task within FUMES. Conditions for success were derived from the real world problem using information supplied by subject matter experts.	Situatedness (Learning tasks)
7	Identify sources of feedback within the real world environment that impact the resolution of the problem.	Real world sources of feedback impacting emergency evacuation at Challenger, such as personnels' ability to maintain awareness of their physical exertion as they moved through the mining environment, were identified by subject matter experts and integrated within FUMES. Participants utilised this feedback to maintain situational awareness as they attempted to achieve resolution.	Situatedness (Learning tasks)
8	Identify the manner in which the real world problem is presented.	Consultation with subject matter experts at Challenger indicated that evacuations were declared using an emergency broadcast system. Auditory cues were employed within FUMES to approximate this functionality such that participants were familiar with the manner in which the problem was presented.	Situatedness (Learning tasks)
9	Identify sources of information within the real world environment which can be utilised to resolve the problem.	Subject matter experts at Challenger identified sources of information within the mining environment that were used to resolve the real world problem, such as the depth markings and escape rise signage used during navigation. These sources of information were embedded within FUMES and subsequently utilised by participants determine their location and navigate towards refuge.	Situatedness (Learning tasks)
10	Identify the objects, activities, events, environmental	The extent to which servicing infrastructure within the mine was used to aid navigation during an	Situatedness (Learning tasks)

	characteristics, and relationships that impact the outcome of the real world problem and concentrate fidelity into these aspects of the simulation.	emergency evacuation was not fully appreciated during situation analysis, and as such, was not implemented within the simulation with high fidelity. This had a negative impact on participant performance, as servicing infrastructure could not be utilised to navigate to refuge within FUMES. Future iterations of FUMES could address this deficiency via the adequate representation of servicing infrastructure within the virtual mining environment.	3D representation, immediate system response, authenticity of the simulation, high visual fidelity (Learning resources)
11	Identify the capabilities of the selected hardware and software platform to authentically and realistically represent the real world problem three-dimensionally. The platform should be capable of providing continuous responses to interaction, identifying collisions between objects, and representing the real world problem with sufficient visual fidelity.	The hardware and software platform selected for FUMES capably supported smooth and seamless interaction with real time lighting and physics for detecting collisions between objects within a 3D environment. This allowed participants to interact in a manner that approximated real world problem-solving activity.	3D representation, immediate system response, authenticity of the simulation, high visual fidelity (Learning resources)

Limitations and Considerations

A number of limitations and considerations relating to situational analysis were also evidenced during the FUMES implementation:

- Omissions or mistakes during situation analysis can impact users' performance. The role of servicing infrastructure as a navigational guide during emergency evacuation was not fully appreciated during situation analysis, and as such, servicing infrastructure was not implemented within FUMES with a great deal of fidelity. This impacted participants' ability to evacuate to refuge during the simulation, and;
- It may not be possible to accurately identify the extent of users' knowledge of the real world problem domain. It was not possible to accurately ascertain the extent of participants' general problem-solving skills during consultation with subject matter experts at Challenger. Thus, while participants' general problem-solving skills were not specifically factored into the design of the simulation, they nonetheless had an impact

on problem-solving performance.

These limitations and considerations can be mitigated by ensuring that the situational analysis of the real world problem is meticulous in its attention to detail. Subject matter experts should be consulted extensively for this purpose in order to minimise the risk of basing design decisions on inaccurate or incomplete information.

8.2 Guidelines for Situational Design Considerations

Situational Design Considerations are incorporated into the design of a 3D problem-based learning environment to accommodate the corresponding overlapping Situational Analytical Factors which have been identified during situation analysis. This is accomplished via the provision of a suitable learning task which engages the user's existing problem-solving knowledge whilst also accommodating the situated nature of the real world problem. Furthermore, the learning resources provided by the 3D simulation environment establish an authentic sense of interaction which approximates the real world problem-solving activity. Analysis of the data elicited during the FUMES implementation identified a series of guidelines relating to this process, which are detailed in Table 8.2 as follows:

Table 8.2. Guidelines for Situational Design Considerations

	Guideline	Implementation example	Link to SUPL Design Framework
12	State a problem in the context of what users already know.	Problem-solving activity within FUMES was situated within a three-dimensional representation of the Challenger mining environment during an underground fire emergency in order to provide participants with a familiar context that was similar to the real world problem. This allowed participants to utilise existing real world knowledge that they had acquired during induction training and through experience with real world evacuations at Challenger.	Structuredness (Learning supports / Learning tasks)
13	Provide sufficient problem structure to allow participants to achieve resolution.	The problem-solving task was too ill-structured for Novice Participants as evidenced via their inability to reach a refuge chamber within the virtual mine without assistance from the Training Staff Member. Novice Participants	Structuredness (Learning supports / Learning tasks)

	required more information to be provided during the statement of the problem to reduce uncertainty and account for their lack of familiarity with the Challenger mining environment during an emergency evacuation. A variable level of structure could have been used to cater to both Novice Participants and Experienced Participants within FUMES.		
14	Identify important elements during the statement of the problem if users are unfamiliar with the real world problem.	The importance of spatial cues was not explicitly stated within FUMES, and as such Novice Participants were not fully aware of their application within within the virtual mining environment. This could have been improved by detailing their significance during the statement of the problem or by providing learning resources in the form of arrows or highlights to help participants identify prominent spatial cues within the virtual mine.	Structuredness (Learning supports / Learning tasks)
15	Embed elements in the problem that are familiar to users.	Building in familiar elements such as refuge chambers, escape rises, and the layout and structure of the mining environment assisted participants to identify the problem-solving context and apply their existing real world knowledge towards resolution.	Domain specificity (Learning supports / Learning tasks)
16	Embed relationships in the problem that are familiar to users.	The relationships between movement speed, terrain inclination, physical exertion, and self-rescuer oxygen consumption within FUMES were consistent with participants existing knowledge of the problem domain. This allowed them to reliably utilise this knowledge to manage the use of their self-rescuer when they encountered smoke within the virtual mine.	Complexity (Learning supports / Learning tasks)
17	Highlight the nature of the activity and the environment in which it will occur during the statement of the problem.	The problem statement clearly articulated that participants would be required to evacuate from a simulated representation of the Challenger mining environment during an underground fire emergency. As such, participants were certain of the context in which the problem-solving task was situated within FUMES and were able to utilise existing knowledge accordingly.	Problem representation (Learning tasks/ Learning resources)

18	Present the user with the obstacles, circumstances, and considerations of the real world problem.	Participants indicated that they needed to contemplate the same issues during problem-solving activity within FUMES that they would during a real world emergency evacuation of the Challenger mine.	Problem representation (Learning tasks/ Learning resources)
19	Associate actions with outcomes in a manner that reflects the nature of the real world problem.	FUMES provided participants with a reliable means to enact existing real world approaches to evacuation as a result of the preservation of the relationships between actions and outcomes. Participants took steps to avoid fire within the virtual mine and equip their self-rescuer when they encountered smoke because they recognised these entities as obstacles to safe evacuation.	Problem representation (Learning tasks/ Learning resources)
20	Vary the obstacles to resolution during each problem-solving instance to provide greater exposure to potential real world problem scenarios.	Each of the three problem-solving instances in FUMES was varied in terms of the user's starting location, the location of the fire, and the severity of the smoke. This encouraged participants to maintain situational awareness as they moved through the virtual mine as they were not always certain of the obstacles between themselves and refuge.	Problem representation (Learning tasks/ Learning resources)
21	Embed the characteristics of the real world problem that relate to resolution within the simulation.	The problem-solving task within FUMES encompassed key elements of the real world problem such as the characteristics of the Challenger mining environment, the function of self-rescuers and escape rises, and the relationship between energy expenditure and self-rescuer oxygen consumption. However, the omission of mining infrastructure within the virtual mine inhibited participants' ability to navigate in the same way they would during an emergency within the real world environment.	Problem representation (Learning tasks/ Learning resources)
22	Structure the problem-solving task to reflect the real world problem.	The problem-solving task within FUMES was structured so participants had their initial location and the location of the fire identified for them, but were not instructed as to how to proceed to refuge. Participants were therefore required to acquire information from within the virtual mining environment to maintain situational awareness and determine a safe route to refuge in much the same way as they would during a real world emergency.	Problem representation, authenticity of information (Learning tasks/ Learning resources)

23	Embed sources of information within the problem-solving task that are available during the real world problem.	Participants utilised the virtual mining environment as a continual source of information for the purposes of maintaining situational awareness and navigating towards refuge. Participants made use of spatial cues such as depth markings and escape rise signage as they moved and orientated themselves for this purpose.	Authenticity of information (Learning tasks/ Learning resources)
24	Provide means of interaction which approximate those used to resolve the real world problem.	FUMES provided participants with the ability to move and orientate within the virtual mine, climb escape rises, change the beam setting on their cap lamp, and equip their self-rescuer freely and at their discretion. This allowed them to enact the series of actions necessary to evacuate during an underground fire emergency in the Challenger mine in order to resolve the problem-solving task.	User control (Learning supports/ Learning resources)
25	Place restrictions on user control if their knowledge of the problem domain is lacking.	During the FUMES implementation, the Training Staff Member was forced to intervene on the behalf of Novice Participants in order to reorientate them when they became lost within the virtual mine. Under such circumstances, Novice Participants could have had their movement restricted to areas of the mine that led to a refuge chamber using barriers within the virtual mine.	User control (Learning supports/ Learning resources)

8.3 Guidelines for Problem-based Learning Design Principles

Problem-based Learning Design Principles are the core tenants within the SUPL Design Framework which guide the learning process in accordance with the Situational Analytical Factors and Situational Design Considerations that have been established. This is achieved via allocating the user control of the learning process, providing them with information and feedback which addresses their needs, assessing their ability to utilise real world resolution strategies, and by prompting them to reflect on their experience in relation to real world application. Analysis of the data elicited during the FUMES implementation identified a series of guidelines relating to this process, which are detailed in Table 8.3 as follows:

Table 8.3. Guidelines for Problem-based Learning Design Principles

	Guideline	Implementation example	Link to SUPL Design Framework
26	Employ feedback which challenges or questions the user when they make mistakes.	Auditory feedback phrased in the form of a question was found to be more effective at inducing corrective changes in participants' behaviour than those phrased as direct instruction.	Feedback (Learning supports/ Learning tasks/ Learning resources)
27	Provide users with feedback which allows them to associate their actions with the outcomes of the problem-solving task.	Participants who came into contact with smoke within FUMES were provided with visual feedback in the form of diminished visibility, and auditory feedback in the form of coughing sounds. This feedback was effective at getting participants to retreat from the smoke and equip their self-rescuer in order to avoid an unsuccessful outcome to the problem.	Feedback (Learning supports/ Learning tasks/ Learning resources)
28	Provide corrective feedback when users appear in need of assistance. Utilise the 3D simulation environment to monitor user behaviour for instances where their progress is inhibited.	Sections of the virtual mine which were far removed from refuge chambers and the routes that led to them contained triggers which would present a corrective auditory cue to the user when their presence was detected. This feedback, which queried whether the user was moving in the right direction, was successful in re-directing users toward refuge.	Feedback (Learning supports/ Learning tasks/ Learning resources)
29	Implement explicit sources of visual and auditory feedback that are not available during the real world problem within the simulation to support the learning process.	During the FUMES implementation, visual feedback in the form of on-screen icons were used to assist participants to recognise the relationships that existed between their movement speed, the inclination of the terrain, and their self-rescuer oxygen consumption. While such explicit forms of feedback were not available during a real world emergency evacuation at Challenger, participants reported that they were a reliable resource during problem-solving activity.	Feedback (Learning supports/ Learning tasks/ Learning resources)
30	Utilise the technical capabilities of the 3D simulation environment to accurately monitor the user's performance.	FUMES was not able to determine whether participants had followed an ideal path to refuge with sufficient accuracy. As such, participants were not always provided with a genuine appraisal of their performance within the simulator. This could have been improved by employing a more sophisticated mechanism that	Feedback, assessment, information (Learning supports/ Learning tasks/ Learning resources)

		measured the extent to which participants deviated from the ideal path to refuge, rather than merely measuring whether or not they adhered to the path.	
31	Let users know whether the solution methods they employ are suitable for real world application.	Assessment mechanisms were employed within FUMES which evaluated user behaviour in relation to accepted practices for reaching refuge within the real world mine. This allowed participants to develop strategies for evacuation during a real world emergency within the Challenger mine.	Assessment (Learning supports/ Learning tasks/ Learning resources)
32	Provide users with information which addresses deficiencies in their knowledge of the problem domain and allows them to utilise the skills that they need to achieve resolution.	The mine layout diagram that was provided to Novice Participants did not fully address their knowledge deficiencies. As such, these participants encountered difficulties navigating within the virtual mining environment, indicating that more extensive information support was required. An interactive map in which Novice Participants could observe their position in relation to the environment around them could have been employed for this purpose.	Information (Learning supports/ Learning tasks/ Learning resources)
33	Integrate the sources of information used to resolve the problem using visual or auditory approximations within the 3D simulation.	Experienced Participants and Novice Participants utilised the virtual mining environment as a source of information during problem-solving activity to maintain situational awareness. The mine layout diagram provided to Novice Participants was not integrated into FUMES due to time constraints during development, however it was recognised that doing so would have provided a more effective source of information. Information (Learning supports/ Learning tasks/ Learning resources)	Information (Learning supports/ Learning tasks/ Learning resources)
34	Enable users to build upon their existing knowledge of the problem domain by allowing them to experiment.	Experienced Participants and Novice Participants were free to determine their own path to refuge within the virtual mine and choose when and where they equipped their self-rescuer in order to safely negotiate smoke. This allowed them to identify an appropriate approach to the problem via experimentation in a manner that was consistent with real world problem-solving activity.	Learner control (Learning supports/ Learning tasks/ Learning resources)
35	Provide the user with the ability to review the	The problem-solving task in FUMES was presented using auditory cues to	Learner control (Learning supports/ Learning tasks/

	information presented in the problem statement at their discretion.	describe the initial conditions of the emergency and instruct participants to evacuate to refuge. However, these auditory cues were played only once and some participants missed the information that they provided which inhibited their ability to engage with the problem. This could have been improved upon by adding a user initiated control, such as a specific button input, to trigger the auditory cue to be played again.	Learning resources)
36	Allow the user to freely manipulate the viewing perspective using an appropriate input device.	Participants were able to freely manipulate the viewing perspective in FUMES using a mouse. This allowed them to acquire information from within the virtual mining environment to maintain situational awareness and evacuate to refuge.	Learner control (Learning supports/ Learning tasks/ Learning resources)
37	Provide multiple examples of the problem which require the user to assume increasing responsibility for their learning.	The problem-solving task in FUMES was structured as a series of three problem-solving instances which became progressively more ill-structured and complex in turn. This forced participants to assume increasing responsibility for the acquisition of information whilst diminishing their reliance on information that was provided explicitly.	Learner control (Learning supports/ Learning tasks/ Learning resources)
38	Tasks should be drawn from users' previous problem-solving experience to encourage reflective thinking.	The problem-solving activity was designed to reflect real world emergency evacuation scenarios at Challenger, whereby participants were required to safely negotiate the mining environment in order to reach refuge. This encouraged Experienced Participants and Novice Participants to relate problem-solving activity in FUMES to their existing experience with emergency evacuations of the Challenger mine due to the common context in which activity was situated.	Reflection (Learning supports/ Learning tasks/ Learning resources)
39	Use explicit cues to prompt reflection for users that lack familiarity with the real world problem.	Text was displayed on screen at the conclusion of the problem which prompted participants to consider how their actions would relate to real world application. These were found to be particularly effective for Novice Participants, as they lacked familiarity with the real world problem required to abstract their experience as effectively as Experienced Participants.	Reflection (Learning supports/ Learning tasks/ Learning resources)

8.4 The Need for Balance

The design elements embodied within the SUPL design framework are not mutually exclusive in that a degree of overlap and interplay exists between them. At times, a state of tension can exist between one or more of these elements in which trade-offs are required. This was clearly evidenced during the FUMES implementation via the need for balance amongst certain design elements.

Novice Participants were observed to struggle during problem-solving activity because the characteristics of the problem-solving task were too closely aligned to those of the real world problem and did not adequately account for their knowledge of the problem domain. Additionally, the ability of the 3D simulation environment to meaningfully respond to user interaction to support the learning process was constrained by the limitations of the technology. Furthermore, the representation of the problem-solving task needed to be proportioned in accordance with both the technical limitations and affordances of the 3D simulation environment.

This demonstrates the need for the authenticity of the problem-solving task to be balanced against learners knowledge of the problem domain, with a view towards enabling learners to successfully achieve resolution. Learners who lack the necessary knowledge to resolve the real world problem need to be supported via a combination of greater problem structure, less problem complexity, feedback, reduced control of the learning process, and learning resources, even if doing so diminishes the authenticity of the problem-solving task in relation to the real world problem.

The technical capabilities of the 3D simulation environment also need to be balanced in relation to the actions that would be used to resolve the real world problem. Appropriated means of interaction must be provided within the confines of the hardware that is available. However, supplementary forms of feedback and learning resources can be provided to account for potential deficiencies using visual and auditory cues. Free and unrestricted interaction using the mechanisms provided within the simulation should be emphasised in order to encourage the learner to develop strategies that are applicable during real world situations.

Accurate and authentic representation of the real world problem requires further balancing in relation to the technical capabilities of the 3D simulation environment and the resources that are

available during development. The key aspects of the real world problem utilised by learners to achieve resolution need to be identified where the resources that are available can be concentrated on their implementation. The selected hardware and software platform must be capable of responding to learner interaction in a manner that approximates real world problem-solving activity in this regard. Means of evaluating and responding to learner behaviour also need to be considered in relation to the technical limitations of the 3D simulation environment in order to allow learners to develop knowledge and strategies that are suitable to real world application.

Collectively, this demonstrates the need for a learning environment which is responsive to users' performance rather than simply a static simulation of the real world. The role of the designer therefore is to understand and appreciate the trade-offs that need to be made in the interests of providing the best learning environment for developing users' understanding of the problem domain. Concessions should be made regarding the authenticity and realism with which the real world problem is represented if it better serves the needs of the user. This could include, for example, restricting the user's control of the learning process and providing instructional support mechanisms which don't exist in the real world when situation analysis has indicated that users' knowledge of the problem domain is inadequate.

8.5 Summary for Guidelines

Based on findings derived from the FUMES implementation, a series of generalised design guidelines have been established to guide the application of the SUPL Design Framework. These guidelines were delineated in concert with Oliver and Herrington's (2001) framework for the design of technology-mediated learning settings in alignment with learning supports, learning tasks, and learning resources (Tables 8.1, 8.2, and 8.3).

The generalised design guidelines presented in these three tables function as a design check-list for 3D, problem-based learning environments via the consideration of Situational Analytical Factors, Situational Design Considerations, and Problem-based Learning Design Principles. Designers can use these guidelines to develop 3D, problem-based learning environments which support knowledge construction and transfer for real world application.

However, the interconnected nature of design considerations in the SUPL Design Framework

may require compromises to be made during the design process in the interests of providing the best learning environment for developing users' understanding of the problem domain. The designer must therefore consider whether concessions need to be made in order to strike an appropriate balance between authenticity and providing a learning environment which is responsive to the needs of users. It is paramount that the product be designed with an emphasis on satisfying the leaning outcomes that have been established, rather than absolute realism in the simulation of the real world problem scenario.

9 Summary and Conclusions

This chapter provides an overview of the research conducted and summarises the findings from the FUMES implementation. It also acknowledges the limitations of the study and describes how the findings can be translated for the benefit of the larger community. Recommendations for further research are also provided before final conclusions are presented.

The study sought to investigate how 3D gaming technologies could be utilised within a problem-based learning framework to develop knowledge for real world application. A review of the literature relating to problem-based learning, computer simulations, and 3D environments identified a series of factors which were significant in this regard. Design considerations were synthesised from these factors and designated Situational Analytical Factors, Situational Design Considerations, and Problem-based Learning Principles within the Simulation, User, and Problem-based Learning (SUPL) Design Framework.

To assess the validity of the SUPL Design Framework, the Fires in Underground Mines Evacuation Simulator (FUMES) was implemented to train personnel in emergency evacuation procedures at the Challenger gold mine in South Australia. Problem-solving activity within FUMES was designed to replicate emergency evacuation scenarios at Challenger in order to elicit existing real world knowledge and facilitate the development of new knowledge which was applicable during real world emergencies. Two groups of participants representing experienced and novice personnel were utilised to ascertain the effectiveness of FUMES as a training platform via a constant comparative analysis of questionnaire, interview, and performance data collected by the simulation.

9.1 Knowledge Transfer Using 3D, Problem-based Learning Environments

This formed the basis of the first research question and addressed the key aspect of the study that related to whether FUMES actually worked as a platform for emergency evacuation training at Challenger. Since direct measures of learning transfer could not be used, three indirect measurement techniques were employed, all of which demonstrated that the product was effective in meeting its learning goals. Both Experienced Participants and Novice Participants

were able to use the simulation environment to develop knowledge for real world emergency evacuations. The ability of Experienced Participants to accurately describe how they were able to use existing knowledge to solve the problem-solving task provided strong evidence for Inverse Transfer of Training. FUMES was validated as a faithful representation of the Challenger mine and effective platform for emergency evacuation training via the Assessment of Fidelity and Operator Opinion measures of learning transfer.

The key findings from this aspect of the study were that for effective learning transfer to occur, the problem-based learning environment needed to elicit users' existing knowledge of the problem domain. This was accomplished using experientially-focussed activity through a realistic depiction of both the problem and the physical and functional characteristics of the environment itself.

Thus, the product was successful and the findings were useful in their emphasis on the quality of the experience and the representation of both the mine and the problem. This formed a baseline for the remainder of the study which sought to explore the more complex question of how best to design these elements through the application of the SUPL Design Framework.

9.2 Validity of the SUPL Design Framework

Chapter 8 provides a list of guidelines for designing 3D problem-based learning environments using the SUPL Design Framework. In summarising these findings, what is clear is the importance of analysis in terms of understanding the needs and capabilities of the user, the intricacies of the real world problem, and the capacity of the 3D simulation environment to approximate meaningful activity. More significant, however, is the interrelatedness and complexity of these elements as components in the final design.

In their need to embrace complexity while ensuring that learning is effectively targeted towards users' skills and expectations, 3D problem-based learning environments must be both reductive and expansive in their design. Authentic tasks are necessary for learning transfer, similarly the environment must accurately reflect the real world. However, simply providing complex resources and activities does not provide a meaningful learning experience. Supports must be integrated that give users the opportunity to tackle the experience in an accessible way whilst embracing this complexity. As mentioned in the previous chapter, this is a balancing act in

which the designer must make choices.

Once a problem has been understood, the role of the designer is to construct a learning experience that represents it. This is not simply a case of translation, the final product must be quite distinct from the real world environment whilst still being instantly recognisable in order to both appeal to, and further nurture the user's knowledge of the problem domain. The designer must accommodate both experienced users and novices and decide how much control of the learning process to cede to them. The degree of fidelity and the areas of the simulation in which it is concentrated must also be contemplated in terms of that which is emphasised, and that which is omitted. The designer must decide where and when to provide information, how to represent it, and what degree of involvement is required on behalf of the user to extract and utilise it. Feedback must be provided targeting the learning needs of users by detecting and responding to instances where knowledge deficiencies are impeding progress whilst also appealing to expectations of the real world problem domain. Metrics for assessing user performance must also be derived using key observable criteria that reflect the complexity of the real world problem.

These are considerations which can be addressed through the application of the SUPL Design Framework. By acknowledging the elements which contribute to the formation and application of problem-solving knowledge in a 3D representation of a real world setting, designers can make informed decisions to best manage problem complexity in a manner that provides users with agency during the learning process. In this manner, the findings of the study emphasise the role of the designer in expanding and contracting the complexity of the problem scenario to provide users with a learning environment in which they can develop applicable real world knowledge.

9.3 Limitations of the Study

The following limitations to the study were identified and acknowledged as having the potential to affect the results:

- The sample size was not large enough to support any detailed statistical analysis. However, trends and patterns were identified within the results which supported the validity of the SUPL Design Framework;

- Of the 41 participants used in the study, only four were female;

- Due to the operational constraints imposed by the Challenger mining environment, direct performance testing of participants was not possible. While the indirect measures of transfer used in the study provided valid methods for evaluating the effectiveness of FUMES, a direct performance comparison may have provided meaningful data for use during analysis, and;

- The researcher was unable to conduct face-to-face interviews with participants as data collection was conducted on-site at the Challenger mining facility;

9.4 Research Translation and Impact

The findings provided by the study can be used by training departments and practitioners of computer-based instruction to instil knowledge that is required to solve real world problems. Recent advances in gaming technologies and the increased availability of low cost, powerful computer hardware allows real world problem-solving scenarios to be represented in a meaningful and cost-effective manner. In this way, instruction can be provided in a controlled learning environment, familiarising learners with the problem prior to real world interaction. This has particular relevance in fields where real world training may not be safe, cost-effective, or feasible, such as defence, search and rescue, or manufacturing.

The SUPL Design Framework provides an effective means for designing such learning environments. It emphases knowledge construction via experiential and user-focussed problem-solving activity that can be transferred to real world situations. By utilising the generalised design guidelines provided by the study, designers of 3D problem-based learning environments can implement the SUPL Design Framework as a simplified design check-list that is accessible to the wider training and educational community.

9.5 Further Research

A number of potential areas for further research were identified during the course of the study:

- Implementation of the SUPL Design Framework in other learning contexts beyond underground mining emergency evacuation training. This could also be extended to include direct performance testing of participants to further explore the effectiveness of

learning transfer;

· Consideration of gaming technologies other than DX Studio for the development of the 3D simulation environment. A methodology for marrying the design requirements which emerge from the SUPL Design Framework and the features of suitable 3D game engines could also be explored to aid development;

· The use of intelligent agents to administer responses to user interaction in a facilitatory capacity during problem-solving activity within the 3D simulation environment. The application of similar methods for use in assessing user performance could also be explored, and;

· An exploration of mechanisms for providing varying levels of learner scaffolding within the 3D simulation environment. This could include the provision of instructional support in different ways in order to appeal to multiple learning styles.

9.6 Conclusions

This study set out to identify the necessary design considerations for developing knowledge for real world application in 3D, problem-based learning environments. The SUPL Design Framework was synthesised from the literature for this purpose and evaluated via the implementation of FUMES in order to satisfy learning requirements that existed within a real world context.

The findings of the study confirmed the presence of learning transfer and established the validity of the SUPL Design Framework. More importantly however, they led to the development of generalised guidelines which could function as a design check-list for practitioners of serious games and computer-based instruction. The findings further highlighted the importance of the role of the designer in making informed decisions, trade-offs, and compromises in order to ensure the best learning environment for developing users' understanding of the problem domain. This emphasises the need for accessible design guidelines to inform the development of 3D, problem-based learning environments that support knowledge construction and transfer.

Chapter 9   **Summary and Conclusions**

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Appendix 1: Participant Information Letter

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Developing knowledge for real world problem scenarios using 3D gaming technology within a problem-based learning framework

Dear Valued Participant,

My name is Michael Garrett and I am a research student at Edith Cowan University currently writing my Phd thesis. My research is concerned with examining the potential benefits of computer based training, and in particular, the application of three dimensional simulation environments within an Occupational Health and Safety context. Previous research in this area has demonstrated the potential benefits of using computer-generated simulation environments for this purpose, with these environments providing a practical, cost-effective, and efficient means of training. My research seeks to build upon this established foundation by identifying a series of design factors that can be used in the development of simulation environments for Occupational Health and Safety training.

My research proposal involves developing a computer simulated representation of a section of the underground mine at Challenger for the purposes of training in the event of an underground fire. The proposed research procedure involves your participation on this computer simulation which will run on a standard desktop personal computer. You will be required to complete a series of exercises within the simulation environment which will assess your ability to locate a refuge chamber given the conditions presented within the virtual mine environment. This process will also involve the use of a microphone headset which will be attached to the computer to record any statements or reactions you may express vocally during your experience with the simulation. Immediately after having used the computer simulation, you will be asked to complete an on-line questionnaire and participate in a telephone interview with myself in relation to your experience with the simulation. The data that is collected as a result of your participation in this study will be collected, analysed and stored in a manner consistent with maintaining your anonymity. After a period of five years, all collected data will be destroyed.

Your involvement in this study has the potential to further advance research within the field of computer based training, and furthermore, assist Dominion Mining in assessing the validity of these training methods in light of their operational requirements. You may also find that your participation in this study increases your familiarity with computer based training environments. No significant risks have been identified with the research proposed by this study. However, if you have previously experienced motion sickness, disorientation, or any other ill effects as a

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result of your experiences with a three dimensional computer environment you are advised not to participate in this study.

It is important to note that your involvement is completely voluntary, and furthermore, that you are able to withdraw from this research at any time if you feel that you no longer wish to participate. Your involvement in this study will not have any bearing on any past or current relationships that you may have with Dominion Mining. I have no involvement with Dominion Mining outside of this research.

Your anonymity in this research project will be maintained via the use of an identification code in place of your name. All information that is collected will be encrypted and stored on a secure computer with access restricted to myself and the supervisors involved with this project. The results of this study may be disseminated in reports, at conferences, or in publications, however, these will not include any information that may identify you as a participant without your consent. While you will not receive any feedback regarding your specific participation in this study, the results of the study will be made freely available on your request.

If you have any queries at all, please don't hesitate to contact those involved as follows:

Michael Garrett
Chief Investigator
+61 8 9470 4481
mjgarret@student.ecu.edu.au

Dr. Mark McMahon
Primary Supervisor
+61 8 9370 6434
m.mcmahon@ecu.edu.au

Prof. Joe Luca
Associate Supervisor
+61 8 9370 6412
j.luca@ecu.edu.au

If you have any concerns or complaints about the research project and wish to talk to an

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independent person, you may contact:

Research Ethics Officer
Edith Cowan University
100 Joondalup Drive
JOONDALUP WA 6027
(08) 6304 2170
research.ethics@ecu.edu.au

This project has been approved by the ECU Human Research Ethics Committee. I thank you for your participation and look forward to your involvement in this project.

Michael Garrett
Edith Cowan University

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Appendix 2: Informed Consent

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Developing knowledge for real world problem scenarios using 3D gaming technology within a problem-based learning framework

I, the undersigned, understand that my participation in the study conducted by Michael Garrett of Edith Cowan University is completely voluntary, and that I am able to withdraw at any time.

My participation involves using a computer simulation of the Challenger underground mining environment, the completion of an on-line questionnaire, and a telephone interview session with Michael Garrett related to my experiences with the computer simulation. My reactions whilst using the simulation will be recorded via audio headset and my actions within the simulation environment will be logged by the simulation software. I will be assessed on my ability to complete an exercise within the simulation environment. The information letter that has been provided to you will explain the research study in more detail.

I further acknowledge that this study is being conducted independently and has no bearing on my standing with Dominion Mining. All information that is provided during your participation in this study will be kept confidential and your identity will not be disclosed without your consent. The information that is collected will only be used for the purposes of this research project in order to determine a set of solid design criteria for the development of computer-generated learning environments.

I have read and understood all the information that has been provided.

If you have any queries at all, please don't hesitate to contact those involved as follows:

Michael Garrett
Chief Investigator
+61 8 9470 4481
mjgarret@student.ecu.edu.au

Dr. Mark McMahon
Primary Supervisor
+61 8 9370 6434
m.mcmahon@ecu.edu.au

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Prof. Joe Luca

Associate Supervisor

+61 8 9370 6412

j.luca@ecu.edu.au

Name: _____

Signature: _____

Date: _____

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Appendix 3: FUMES Reference Sheet

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Keyboard Controls
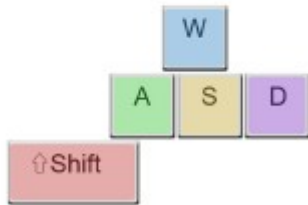
w = move forward
a = sidestep left
s = move backwards
d = side step right

Shift (held) = run

r = activate self-rescuer
c = change cap lamp beam setting
e = climb escape rise

Icons

Illuminated when your self-rescuer is active

Illuminated when you smell stench gas

Illuminated when an escape rise can be climbed

Illuminated when your walkie talkie is providing information

Indicates the beam setting of your cap lamp

Indicates the physical effort you are currently exerting

Indicates the speed at which you are moving

Indicates the slope of the ground you are moving over

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Appendix 4: Mine Layout Diagram

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Appendix 5: Experienced Participant Questionnaire

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List of Definitions

'Training scenarios' refers to the series of 3 tasks that you were required to complete within the FUMES simulation.

'3D environment' refers to the three-dimensional environment generated by the computer that you moved through and interacted with.

Questionnaire

1.1) Please enter your full name

1.2) I feel confident using computers (strongly disagree, disagree, neutral, agree, or strongly agree)?

1.3) I am comfortable using a mouse and keyboard (strongly disagree, disagree, neutral, agree, or strongly agree)?

1.4) I have previous experience with computer games (strongly disagree, disagree, neutral, agree, or strongly agree)?

1.5) I have previous experience with computer software which displays three-dimensional environments (strongly disagree, disagree, neutral, agree, or strongly agree)?

2.1) I have previous experience with emergency evacuations of the Challenger mine (strongly disagree, disagree, neutral, agree, or strongly agree)?

2.2) I have previous experience with emergency evacuations of other underground mines (strongly disagree, disagree, neutral, agree, or strongly agree)?

2.3) I relied on my knowledge of the Challenger mine and its emergency evacuation procedures to complete the training scenarios (strongly disagree, disagree, neutral, agree, or strongly agree)?

2.4) I relied on my general problem-solving skills to complete the training scenarios (strongly

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disagree, disagree, neutral, agree, or strongly agree)?

3.1) The training scenarios effectively represented real world emergency evacuations at Challenger (strongly disagree, disagree, neutral, agree, or strongly agree)?

3.2) Obstacles in the training scenarios were consistent with real world emergency evacuations at Challenger (strongly disagree, disagree, neutral, agree, or strongly agree)?

3.3) I had to consider the same things during the training scenarios that I would during a real world emergency evacuation at Challenger (strongly disagree, disagree, neutral, agree, or strongly agree)?

3.4) The behaviour of the self-rescuer and cap lamp were consistent with real world emergency evacuations at Challenger (strongly disagree, disagree, neutral, agree, or strongly agree)?

3.5) The training scenarios seemed familiar to me (strongly disagree, disagree, neutral, agree, or strongly agree)?

4.1) I knew what to do and where to go at the beginning of each training scenario (strongly disagree, disagree, neutral, agree, or strongly agree)?

4.2) The way to complete each training scenario was clear to me (strongly disagree, disagree, neutral, agree, or strongly agree)?

5.1) Before using the simulation, I knew the procedure for an emergency evacuation at Challenger (strongly disagree, disagree, neutral, agree, or strongly agree)?

5.2) Before using the simulation, I knew the layout and structure of the Challenger mine and could confidently travel from one location to another (strongly disagree, disagree, neutral, agree, or strongly agree)?

5.3) Before using the simulation, I knew where the refuge chambers and escape rises were located in the Challenger mine (strongly disagree, disagree, neutral, agree, or strongly agree)?

6.1) Before using the simulation, I knew the correct procedure for using my self-rescuer during

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an emergency evacuation (strongly disagree, disagree, neutral, agree, or strongly agree)?

6.2) Before using the simulation, I knew how long the oxygen in a self-rescuer would last for (strongly disagree, disagree, neutral, agree, or strongly agree)?

6.3) Before using the simulation, I knew how to make the oxygen supply in a self-rescuer last as long as possible (strongly disagree, disagree, neutral, agree, or strongly agree)?

6.4) Before using the simulation, I knew when to use an escape rise during an emergency evacuation (strongly disagree, disagree, neutral, agree, or strongly agree)?

7.1) Before using the simulation, I knew what stench gas was used for at Challenger (strongly disagree, disagree, neutral, agree, or strongly agree)?

7.2) I am good at solving problems (strongly disagree, disagree, neutral, agree, or strongly agree)?

7.3) I can solve problems that I'm not familiar with (strongly disagree, disagree, neutral, agree, or strongly agree)?

8.1) Choose the following statement which best describes your experience with the simulation:

   a) I was provided with all the information I needed at the beginning of each training
   scenario to safely evacuate from the mine;

   b) I was provided with some information at the beginning of each training scenario, but
   some important pieces of information were missing. I had to fill in these gaps myself
   in order to safely evacuate from the mine, or;

   c) I was provided with little information at the beginning of each training scenario. I had
   to gather information from the environment myself in order to safely evacuate   from
   the mine.

8.2) The simulation clearly represented the Challenger mine (strongly disagree, disagree, neutral, agree, or strongly agree)?

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8.3) The training scenarios clearly represented an emergency evacuation of the Challenger mine (strongly disagree, disagree, neutral, agree, or strongly agree)?

8.4) The training scenarios required me to do things that I would have to do during a real emergency evacuation of the Challenger mine (strongly disagree, disagree, neutral, agree, or strongly agree)?

8.5) Moving up the decline required more physical effort than moving down the decline within the simulation (strongly disagree, disagree, neutral, agree, or strongly agree)?

9.1) Running required more physical effort than walking within the simulation (strongly disagree, disagree, neutral, agree, or strongly agree)?

9.2) Climbing an escape rise required a great deal of physical effort within the simulation (strongly disagree, disagree, neutral, agree, or strongly agree)?

9.3) I had to be aware of my physical effort when using my self-rescuer within the simulation (strongly disagree, disagree, neutral, agree, or strongly agree)?

9.4) Stench gas was released during the emergency evacuations within the simulation (strongly disagree, disagree, neutral, agree, or strongly agree)?

9.5) The smoke got thicker the closer I got to a fire within the simulation (strongly disagree, disagree, neutral, agree, or strongly agree)?

10.1) I had a choice of refuge chambers to evacuate to within the simulation (strongly disagree, disagree, neutral, agree, or strongly agree)?

10.2) Each training scenario had more than one possible outcome (strongly disagree, disagree, neutral, agree, or strongly agree)?

10.3) My actions determined the outcome of each training scenario (strongly disagree, disagree, neutral, agree, or strongly agree)?

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10.4) I needed to know the layout and structure of the Challenger mine in order to complete the training scenarios (strongly disagree, disagree, neutral, agree, or strongly agree)?

10.5) I needed to know the emergency evacuation procedures at Challenger in order to complete the training scenarios (strongly disagree, disagree, neutral, agree, or strongly agree)?

11.1) I needed to make immediate decisions in order to complete the training scenarios (strongly disagree, disagree, neutral, agree, or strongly agree)?

11.2) I felt motivated to complete the training scenarios (strongly disagree, disagree, neutral, agree, or strongly agree)?

11.3) I felt a sense of urgency or excitement whilst completing the training scenarios (strongly disagree, disagree, neutral, agree, or strongly agree)?

12.1) I was confident that I could complete each training scenario (strongly disagree, disagree, neutral, agree, or strongly agree)?

13.1) The 3D environment looked realistic (strongly disagree, disagree, neutral, agree, or strongly agree)?

13.2) I got an accurate sense of space as I was moving around the 3D environment (strongly disagree, disagree, neutral, agree, or strongly agree)?

13.3) The size and scale of the mine was represented accurately by the 3D environment (strongly disagree, disagree, neutral, agree, or strongly agree)?

13.4) I knew whether I was moving uphill, downhill, or on a level surface within the 3D environment (strongly disagree, disagree, neutral, agree, or strongly agree)?

14.1) I could determine the locations of objects and how to reach them within the 3D environment (strongly disagree, disagree, neutral, agree, or strongly agree)?

14.2) I had a clear sense of my location within the 3D environment (strongly disagree, disagree, neutral, agree, or strongly agree)?

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14.3) I knew when and where to use my self-rescuer within the 3D environment (strongly disagree, disagree, neutral, agree, or strongly agree)?

14.4) I knew when and where to use an escape rise within the 3D environment (strongly disagree, disagree, neutral, agree, or strongly agree)?

15.1) The physical effort I expended within the simulation was affected by the slope of the terrain (strongly disagree, disagree, neutral, agree, or strongly agree)?

15.2) The physical effort I expended within the simulation affected the rate at which the oxygen in my self-rescuer was used (strongly disagree, disagree, neutral, agree, or strongly agree)?

15.3) The training scenarios provided a clear understanding as to correct evacuation procedure during an emergency (strongly disagree, disagree, neutral, agree, or strongly agree)?

15.4) The signs attached to the walls within the 3D environment indicated which level I was on and the direction of escape rises (strongly disagree, disagree, neutral, agree, or strongly agree)?

16.1) Lighting and shadows within the 3D environment were consistent with the real world mine (strongly disagree, disagree, neutral, agree, or strongly agree)?

16.2) The cap lamp provided me with enough light to effectively complete the training scenarios (strongly disagree, disagree, neutral, agree, or strongly agree)?

16.3) Overall, the 3D environment looked like the real world mine (strongly disagree, disagree, neutral, agree, or strongly agree)?

16.4) I was able to identify objects within the 3D environment by looking at them (strongly disagree, disagree, neutral, agree, or strongly agree)?

17.1) I was able to identify objects within the 3D environment from a distance (strongly disagree, disagree, neutral, agree, or strongly agree)?
17.2) I could determine the distance and direction of a fire within the 3D environment (strongly disagree, disagree, neutral, agree, or strongly agree)?

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17.3) I felt detached from the real world as I was using the simulation (strongly disagree, disagree, neutral, agree, or strongly agree)?

17.4) I seemed to move realistically within the 3D environment (strongly disagree, disagree, neutral, agree, or strongly agree)?

18.1) I felt as though I was physically present within the 3D environment (strongly disagree, disagree, neutral, agree, or strongly agree)?

18.2) The 3D environment responded immediately to my mouse and keyboard input (strongly disagree, disagree, neutral, agree, or strongly agree)?

19.1) The 3D environment displayed smoothly and seamlessly (strongly disagree, disagree, neutral, agree, or strongly agree)?

20.1) I was able to effectively interact with objects within the 3D environment (strongly disagree, disagree, neutral, agree, or strongly agree)?

20.2) The keyboard and mouse allowed me to move and interact effectively within the 3D environment (strongly disagree, disagree, neutral, agree, or strongly agree)?

20.3) I knew when I had walked or run into objects within the 3D environment (strongly disagree, disagree, neutral, agree, or strongly agree)?

20.4) I knew when my movement was obstructed by a solid object within the 3D environment (strongly disagree, disagree, neutral, agree, or strongly agree)?

21.1) I learned something during the training scenarios (strongly disagree, disagree, neutral, agree, or strongly agree)?

21.2) I felt in control of my learning during the training scenarios (strongly disagree, disagree, neutral, agree, or strongly agree)?

21.3) The simulation controlled what I learned during the training scenarios (strongly disagree, disagree, neutral, agree, or strongly agree)?

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21.4) Information provided by the walkie talkie helped me know what to do and where to go during the training scenarios (strongly disagree, disagree, neutral, agree, or strongly agree)?

22.1) Information provided by the walkie talkie helped me when I encountered problems during the training scenarios (strongly disagree, disagree, neutral, agree, or strongly agree)?

22.2) The mining environment provided information that I used to complete the training scenarios (strongly disagree, disagree, neutral, agree, or strongly agree)?

22.3) The icons at the bottom of the screen provided me with information that I used to complete the training scenarios (strongly disagree, disagree, neutral, agree, or strongly agree)?

23.1) The information I was provided with within during the simulation was relevant to the training scenarios (strongly disagree, disagree, neutral, agree, or strongly agree)?

23.2) The importance of the walkie talkie was made clear to me before beginning the training scenarios (strongly disagree, disagree, neutral, agree, or strongly agree)?

23.3) The importance of the icons at the bottom of the screen was made clear to me before beginning the training scenarios (strongly disagree, disagree, neutral, agree, or strongly agree)?

23.4) The importance of the depth markings and escape rise signs was made clear to me before beginning the training scenarios (strongly disagree, disagree, neutral, agree, or strongly agree)?

24.1) My experience with the simulation could be useful in future emergency evacuation situations at Challenger (strongly disagree, disagree, neutral, agree, or strongly agree)?

24.2) My experience with the simulation could be useful in future emergency evacuation situations in other underground mines (strongly disagree, disagree, neutral, agree, or strongly agree)?

24.3) I was given an opportunity to think about what I had done after each training scenario (strongly disagree, disagree, neutral, agree, or strongly agree)?

24.4) The simulation prompted me to think about specific things that I did during each training scenario (strongly disagree, disagree, neutral, agree, or strongly agree)?

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24.5) The simulation provided me with feedback in response to my actions (strongly disagree, disagree, neutral, agree, or strongly agree)?

25.1) The walkie talkie kept me moving in the right direction within the 3D environment (strongly disagree, disagree, neutral, agree, or strongly agree)?

25.2) The walkie talkie let me know when I was getting too close to a fire within the 3D environment (strongly disagree, disagree, neutral, agree, or strongly agree)?

25.3) The walkie talkie told me when I needed to use my self-rescuer within the 3D environment (strongly disagree, disagree, neutral, agree, or strongly agree)?

25.4) The simulation provided me with feedback that was relevant to my actions (strongly disagree, disagree, neutral, agree, or strongly agree)?

25.5) The simulation provided me with feedback that was relevant to the training scenario (strongly disagree, disagree, neutral, agree, or strongly agree)?

26.1) I knew how fast I was moving within the 3D environment (strongly disagree, disagree, neutral, agree, or strongly agree)?

26.2) I knew how much physical effort I was expending within the 3D environment (strongly disagree, disagree, neutral, agree, or strongly agree)?

27.1) I knew when I could climb an escape rise within the 3D environment (strongly disagree, disagree, neutral, agree, or strongly agree)?

27.2) I knew when my self-rescuer was activated within the 3D environment (strongly disagree, disagree, neutral, agree, or strongly agree)?

27.3) I knew whether my cap lamp was set to low or high beam setting within the 3D environment (strongly disagree, disagree, neutral, agree, or strongly agree)?

28.1) The walkie talkie prompted me to change what I was doing within the 3D environment (strongly disagree, disagree, neutral, agree, or strongly agree)?

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28.2) The simulation would be a valuable training tool for emergency evacuation procedures at Challenger (strongly disagree, disagree, neutral, agree, or strongly agree)?

28.3) The simulation accurately represented the emergency evacuation procedure at Challenger during a fire underground (strongly disagree, disagree, neutral, agree, or strongly agree)?

28.4) The simulation had the necessary features for emergency evacuation training at Challenger (strongly disagree, disagree, neutral, agree, or strongly agree)?

29.1) Using the simulation could improve the performance of mining personnel during an emergency evacuation at Challenger (strongly disagree, disagree, neutral, agree, or strongly agree)?

29.2) The simulation accurately represented the Challenger mining environment (strongly disagree, disagree, neutral, agree, or strongly agree)?

29.3) The simulation accurately represented the environmental conditions at Challenger during a fire underground (strongly disagree, disagree, neutral, agree, or strongly agree)?

29.4) Please provide any additional comments or feedback in relation to your experience with the FUMES simulation below.

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Appendix 6: Novice Participant Questionnaire

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List of Definitions

'Training scenarios' refers to the series of 3 tasks that you were required to complete within the FUMES simulation.

'3D environment' refers to the three-dimensional environment generated by the computer that you moved through and interacted with.

Questionnaires

1.1) Please enter your full name

1.2) I feel confident using computers (strongly disagree, disagree, neutral, agree, or strongly agree)?

1.3) I am comfortable using a mouse and keyboard (strongly disagree, disagree, neutral, agree, or strongly agree)?

1.4) I have previous experience with computer games (strongly disagree, disagree, neutral, agree, or strongly agree)?

1.5) I have previous experience with computer software which displays three-dimensional environments (strongly disagree, disagree, neutral, agree, or strongly agree)?

2.1) I have previous experience with emergency evacuations of the Challenger mine (strongly disagree, disagree, neutral, agree, or strongly agree)?

2.2) I have previous experience with emergency evacuations of other underground mines (strongly disagree, disagree, neutral, agree, or strongly agree)?

2.3) I relied on my knowledge of the Challenger mine and its emergency evacuation procedures to complete the training scenarios (strongly disagree, disagree, neutral, agree, or strongly agree)?

2.4) I relied on my general problem-solving skills to complete the training scenarios (strongly

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disagree, disagree, neutral, agree, or strongly agree)?

3.1) I knew what to do and where to go at the beginning of each training scenario (strongly disagree, disagree, neutral, agree, or strongly agree)?

3.2) The way to complete each training scenario was clear to me (strongly disagree, disagree, neutral, agree, or strongly agree)?

3.3) The training scenarios seemed familiar to me (strongly disagree, disagree, neutral, agree, or strongly agree)?

4.1) Before using the simulation, I knew the procedure for an emergency evacuation at Challenger (strongly disagree, disagree, neutral, agree, or strongly agree)?

4.2) Before using the simulation, I knew the layout and structure of the Challenger mine and could confidently travel from one location to another (strongly disagree, disagree, neutral, agree, or strongly agree)?

4.3) Before using the simulation, I knew where the refuge chambers and escape rises were located in the Challenger mine (strongly disagree, disagree, neutral, agree, or strongly agree)?

5.1) Before using the simulation, I knew the correct procedure for using my self-rescuer during an emergency evacuation (strongly disagree, disagree, neutral, agree, or strongly agree)?

5.2) Before using the simulation, I knew how long the oxygen in a self-rescuer would last for (strongly disagree, disagree, neutral, agree, or strongly agree)?

5.3) Before using the simulation, I knew how to make the oxygen supply in a self-rescuer last as long as possible (strongly disagree, disagree, neutral, agree, or strongly agree)?

5.4) Before using the simulation, I knew when to use an escape rise during an emergency evacuation (strongly disagree, disagree, neutral, agree, or strongly agree)?

6.1) Before using the simulation, I knew what stench gas was used for at Challenger (strongly disagree, disagree, neutral, agree, or strongly agree)?

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6.2) I am good at solving problems (strongly disagree, disagree, neutral, agree, or strongly agree)?

6.3) I can solve problems that I'm not familiar with (strongly disagree, disagree, neutral, agree, or strongly agree)?

7.1) Choose the following statement which best describes your experience with the simulation:

> a) I was provided with all the information I needed at the beginning of each training scenario to safely evacuate from the mine;

> b) I was provided with some information at the beginning of each training scenario, but some important pieces of information were missing. I had to fill in these gaps myself in order to safely evacuate from the mine, or;

> c) I was provided with little information at the beginning of each training scenario. I had to gather information from the environment myself in order to safely evacuate from the mine.

7.2) The simulation clearly represented the Challenger mine (strongly disagree, disagree, neutral, agree, or strongly agree)?

7.3) The training scenarios clearly represented an emergency evacuation of the Challenger mine (strongly disagree, disagree, neutral, agree, or strongly agree)?

7.4) The training scenarios required me to do things that I would have to do during a real emergency evacuation of the Challenger mine (strongly disagree, disagree, neutral, agree, or strongly agree)?

7.5) Moving up the decline required more physical effort than moving down the decline within the simulation (strongly disagree, disagree, neutral, agree, or strongly agree)?

8.1) Running required more physical effort than walking within the simulation (strongly disagree, disagree, neutral, agree, or strongly agree)?

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8.2) Climbing an escape rise required a great deal of physical effort within the simulation (strongly disagree, disagree, neutral, agree, or strongly agree)?

8.3) I had to be aware of my physical effort when using my self-rescuer within the simulation (strongly disagree, disagree, neutral, agree, or strongly agree)?

8.4) Stench gas was released during the emergency evacuations within the simulation (strongly disagree, disagree, neutral, agree, or strongly agree)?

8.5) The smoke got thicker the closer I got to a fire within the simulation (strongly disagree, disagree, neutral, agree, or strongly agree)?

9.1) I had a choice of refuge chambers to evacuate to within the simulation (strongly disagree, disagree, neutral, agree, or strongly agree)?

9.2) Each training scenario had more than one possible outcome (strongly disagree, disagree, neutral, agree, or strongly agree)?

9.3) My actions determined the outcome of each training scenario (strongly disagree, disagree, neutral, agree, or strongly agree)?

9.4) I needed to know the layout and structure of the Challenger mine in order to complete the training scenarios (strongly disagree, disagree, neutral, agree, or strongly agree)?

9.5) I needed to know the emergency evacuation procedures at Challenger in order to complete the training scenarios (strongly disagree, disagree, neutral, agree, or strongly agree)?

10.1) I needed to make immediate decisions in order to complete the training scenarios (strongly disagree, disagree, neutral, agree, or strongly agree)?

10.2) I felt motivated to complete the training scenarios (strongly disagree, disagree, neutral, agree, or strongly agree)?

10.3) I felt a sense of urgency or excitement whilst completing the training scenarios (strongly disagree, disagree, neutral, agree, or strongly agree)?

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11.1) I was confident that I could complete each training scenario (strongly disagree, disagree, neutral, agree, or strongly agree)?

12.1) The 3D environment looked realistic (strongly disagree, disagree, neutral, agree, or strongly agree)?

12.2) I got an accurate sense of space as I was moving around the 3D environment (strongly disagree, disagree, neutral, agree, or strongly agree)?

12.3) The size and scale of the mine was represented accurately by the 3D environment (strongly disagree, disagree, neutral, agree, or strongly agree)?

12.4) I knew whether I was moving uphill, downhill, or on a level surface within the 3D environment (strongly disagree, disagree, neutral, agree, or strongly agree)?

13.1) I could determine the locations of objects and how to reach them within the 3D environment (strongly disagree, disagree, neutral, agree, or strongly agree)?

13.2) I had a clear sense of my location within the 3D environment (strongly disagree, disagree, neutral, agree, or strongly agree)?

13.3) I knew when and where to use my self-rescuer within the 3D environment (strongly disagree, disagree, neutral, agree, or strongly agree)?

13.4) I knew when and where to use an escape rise within the 3D environment (strongly disagree, disagree, neutral, agree, or strongly agree)?

14.1) The physical effort I expended within the simulation was affected by the slope of the terrain (strongly disagree, disagree, neutral, agree, or strongly agree)?

14.2) The physical effort I expended within the simulation affected the rate at which the oxygen in my self-rescuer was used (strongly disagree, disagree, neutral, agree, or strongly agree)?

14.3) The training scenarios provided a clear understanding as to correct evacuation procedure during an emergency (strongly disagree, disagree, neutral, agree, or strongly agree)?

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14.4) The signs attached to the walls within the 3D environment indicated which level I was on and the direction of escape rises (strongly disagree, disagree, neutral, agree, or strongly agree)?

15.1) Lighting and shadows within the 3D environment were consistent with the real world mine (strongly disagree, disagree, neutral, agree, or strongly agree)?

15.2) The cap lamp provided me with enough light to effectively complete the training scenarios (strongly disagree, disagree, neutral, agree, or strongly agree)?

15.3) Overall, the 3D environment looked like the real world mine (strongly disagree, disagree, neutral, agree, or strongly agree)?

15.4) I was able to identify objects within the 3D environment by looking at them (strongly disagree, disagree, neutral, agree, or strongly agree)?

16.1) I was able to identify objects within the 3D environment from a distance (strongly disagree, disagree, neutral, agree, or strongly agree)?

16.2) I could determine the distance and direction of a fire within the 3D environment (strongly disagree, disagree, neutral, agree, or strongly agree)?

16.3) I felt detached from the real world as I was using the simulation (strongly disagree, disagree, neutral, agree, or strongly agree)?

16.4) I seemed to move realistically within the 3D environment (strongly disagree, disagree, neutral, agree, or strongly agree)?

17.1) I felt as though I was physically present within the 3D environment (strongly disagree, disagree, neutral, agree, or strongly agree)?

17.2) The 3D environment responded immediately to my mouse and keyboard input (strongly disagree, disagree, neutral, agree, or strongly agree)?

18.1) The 3D environment displayed smoothly and seamlessly (strongly disagree, disagree, neutral, agree, or strongly agree)?

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19.1) I was able to effectively interact with objects within the 3D environment (strongly disagree, disagree, neutral, agree, or strongly agree)?

19.2) The keyboard and mouse allowed me to move and interact effectively within the 3D environment (strongly disagree, disagree, neutral, agree, or strongly agree)?

19.3) I knew when I had walked or run into objects within the 3D environment (strongly disagree, disagree, neutral, agree, or strongly agree)?

19.4) I knew when my movement was obstructed by a solid object within the 3D environment (strongly disagree, disagree, neutral, agree, or strongly agree)?

20.1) I learned something during the training scenarios (strongly disagree, disagree, neutral, agree, or strongly agree)?

20.2) I felt in control of my learning during the training scenarios (strongly disagree, disagree, neutral, agree, or strongly agree)?

20.3) The simulation controlled what I learned during the training scenarios (strongly disagree, disagree, neutral, agree, or strongly agree)?

20.4) Information provided by the walkie talkie helped me know what to do and where to go during the training scenarios (strongly disagree, disagree, neutral, agree, or strongly agree)?

21.1) Information provided by the walkie talkie helped me when I encountered problems during the training scenarios (strongly disagree, disagree, neutral, agree, or strongly agree)?

21.2) The mining environment provided information that I used to complete the training scenarios (strongly disagree, disagree, neutral, agree, or strongly agree)?

21.3) The icons at the bottom of the screen provided me with information that I used to complete the training scenarios (strongly disagree, disagree, neutral, agree, or strongly agree)?

22.1) The information I was provided with within during the simulation was relevant to the training scenarios (strongly disagree, disagree, neutral, agree, or strongly agree)?

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22.2) The importance of the walkie talkie was made clear to me before beginning the training scenarios (strongly disagree, disagree, neutral, agree, or strongly agree)?

22.3) The importance of the icons at the bottom of the screen was made clear to me before beginning the training scenarios (strongly disagree, disagree, neutral, agree, or strongly agree)?

22.4) The importance of the depth markings and escape rise signs was made clear to me before beginning the training scenarios (strongly disagree, disagree, neutral, agree, or strongly agree)?

23.1) My experience with the simulation could be useful in future emergency evacuation situations at Challenger (strongly disagree, disagree, neutral, agree, or strongly agree)?

23.2) My experience with the simulation could be useful in future emergency evacuation situations in other underground mines (strongly disagree, disagree, neutral, agree, or strongly agree)?

23.3) I was given an opportunity to think about what I had done after each training scenario (strongly disagree, disagree, neutral, agree, or strongly agree)?

23.4) The simulation prompted me to think about specific things that I did during each training scenario (strongly disagree, disagree, neutral, agree, or strongly agree)?

23.5) The simulation provided me with feedback in response to my actions (strongly disagree, disagree, neutral, agree, or strongly agree)?

24.1) The walkie talkie kept me moving in the right direction within the 3D environment (strongly disagree, disagree, neutral, agree, or strongly agree)?

24.2) The walkie talkie let me know when I was getting too close to a fire within the 3D environment (strongly disagree, disagree, neutral, agree, or strongly agree)?

24.3) The walkie talkie told me when I needed to use my self-rescuer within the 3D environment (strongly disagree, disagree, neutral, agree, or strongly agree)?

24.4) The simulation provided me with feedback that was relevant to my actions (strongly

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disagree, disagree, neutral, agree, or strongly agree)?

24.5) The simulation provided me with feedback that was relevant to the training scenario (strongly disagree, disagree, neutral, agree, or strongly agree)?

25.1) I knew how fast I was moving within the 3D environment (strongly disagree, disagree, neutral, agree, or strongly agree)?

25.2) I knew how much physical effort I was expending within the 3D environment (strongly disagree, disagree, neutral, agree, or strongly agree)?

26.1) I knew when I could climb an escape rise within the 3D environment (strongly disagree, disagree, neutral, agree, or strongly agree)?

26.2) I knew when my self-rescuer was activated within the 3D environment (strongly disagree, disagree, neutral, agree, or strongly agree)?

26.3) I knew whether my cap lamp was set to low or high beam setting within the 3D environment (strongly disagree, disagree, neutral, agree, or strongly agree)?

27.1) The walkie talkie prompted me to change what I was doing within the 3D environment (strongly disagree, disagree, neutral, agree, or strongly agree)?

27.2) The simulation would be a valuable training tool for emergency evacuation procedures at Challenger (strongly disagree, disagree, neutral, agree, or strongly agree)?

27.3) The simulation accurately represented the emergency evacuation procedure at Challenger during a fire underground (strongly disagree, disagree, neutral, agree, or strongly agree)?

27.4) The simulation had the necessary features for emergency evacuation training at Challenger (strongly disagree, disagree, neutral, agree, or strongly agree)?

28.1) Using the simulation could improve the performance of mining personnel during an emergency evacuation at Challenger (strongly disagree, disagree, neutral, agree, or strongly agree)?

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28.2) Please provide any additional comments or feedback in relation to your experience with the FUMES simulation below.

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Appendix 7: Experienced Participant Interview

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Interview Questions

1) Briefly describe your background at Challenger. How long have you worked at Challenger for?

2) Do you have previous experience in underground mining before Challenger? If so, please describe.

3) What value would the simulator have for real world emergency evacuation training?

4) How similar was the simulator to the real world mining environment?

5) Was your real world experience at Challenger of help to you when using the simulator?

6) How well did the simulator respond to your actions?

7) Did the simulator let you know how well you were performing as you progressed through the scenarios?

8) Did the simulator require you to discover more information on your own as you progressed through the scenarios?

9) Were you provided with all the information you needed to successfully complete the scenarios?

10) Were you prompted to think about your experience within the simulator?

11) How physically similar was the virtual mine in comparison to the real world mine?

12) Did the virtual mine function in the same way as the real world mine?

13) Did the simulation improve your knowledge of the layout and structure of the Challenger mine?

14) How was your movement speed, physical exertion, and self-rescuer oxygen consumption

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related?

15) Were the visuals of a high enough quality to complete the training scenarios? Did any visual aspects of the simulator need to be better in this regard?

16) Did you feel immersed in an emergency situation whilst using the simulator?

17) Did you feel as though you had a physical presence in the virtual mine?

18) How well were you able to move and interact within the simulation? Were you limited in any way?

19) What previous experience were you able to draw upon to assist you during the simulation?

20) What things were unknown or uncertain to you during the training scenarios?

21) What things did you need to consider during the training scenarios?

22) What information did you need to know in order to complete the training scenarios successfully?

23) Could you identify any objects or actions that were interrelated during the simulation?

24) How did the level of physical effort required change as you moved through the virtual mine?

25) How did physical effort affect your breathing?

26) How did physical effort affect the rate at which oxygen in your self-rescuer was consumed?

27) How did your existing knowledge of the Challenger mine and its emergency evacuation procedures affect your performance within the simulator?

28) What was you strategy for completing the training scenarios?

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29) Which aspects of the training scenarios seemed clear or familiar to you?

30) What knowledge of the Challenger mine did you posses prior to using the simulator?

31) What knowledge of emergency evacuation procedures did you posses prior to using the simulator?

32) How did you perceive the training scenarios as a result of this pre-existing knowledge?

33) How quickly did you recognise the virtual environment as the Challenger mine?

34) How quickly did you realise that you were in an emergency evacuation scenario?

35) How clear was the relationship between movement speed, physical effort, and oxygen consumption when using the self-rescuer?

36) Were the training scenarios worthwhile and meaningful?

37) What skills did you use to complete the training scenarios?

38) What was the ideal route to take to a refuge chamber during the training scenarios?

39) How well would someone need to know the Challenger mine and its emergency evacuation procedures in order to successfully complete the training scenarios?

40) What motivated you to complete the training scenarios?

41) Were the methods for successfully completing the training scenarios acceptable given your experience in the real mine?

42) What information were you aware of at the beginning of each training scenario? How did you acquire this information?

43) How did the simulator respond to your actions? What feedback was provided?

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44) Was the feedback information provided by the simulation authentic in relation to the real world mine?

45) Was the manner in which feedback was provided authentic in relation to the real world mine?

46) Did the simulation fairly and accurately assess the outcome of each training scenario?

47) Did the simulation reliably assess the outcome of each training scenario?

48) Did the simulation assess the outcome of each training scenario in a manner that was consistent with measures used in the real world mine?

49) To what extent did you feel in control of the learning process?

50) What previous knowledge and experience did you find useful during the training scenarios?

51) Did the simulation guide you towards learning things that were important for emergency evacuations at Challenger?

52) What information did you use to complete the training scenarios?

53) Did the simulation identify important information for you?

54) What new knowledge have you acquired as a result of using the simulation?

55) What aspects of the training scenarios do you think led to the development of new knowledge?

56) What future applications do you think your newly acquired knowledge may have?

57) Was the way in which the walkie talkie was used in the simulation consistent with real world emergency evacuations at Challenger?

58) Was the information provided by the walkie talkie at the beginning of each training scenario

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consistent with the information that would be provided during an emergency evacuation at Challenger?

59) Which of your senses were provided with information at the beginning of each training scenario?

60) What can you recall about your experience with the simulator?

61) Describe the beginning of each training scenario.

Appendix 8: Novice Participant Interview

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Interview Questions

1) Briefly describe your background at Challenger. How long have you worked at Challenger for?

2) Do you have previous experience in underground mining before Challenger? If so, please describe.

3) What value would the simulator have for real world emergency evacuation training?

4) Do you think you would have found it easier to use the simulator if you had more experience in the real world mine?

5) How well did the simulator respond to your actions?

6) Did the simulator let you know how well you were performing as you progressed through the scenarios?

7) Did the simulator require you to discover more information on your own as you progressed through the scenarios?

8) Were you provided with all the information you needed to successfully complete the scenarios?

9) Were you prompted to think about your experience within the simulator?

10) How physically similar was the virtual mine in comparison to the real world mine?

11) Did the virtual mine function in the same way as the real world mine?

12) Did the simulation improve your knowledge of the layout and structure of the Challenger mine?

13) How was your movement speed, physical exertion, and self-rescuer oxygen consumption related?

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14) Were the visuals of a high enough quality to complete the training scenarios? Did any visual aspects of the simulator need to be better in this regard?

15) Did you feel immersed in an emergency situation whilst using the simulator?

16) Did you feel as though you had a physical presence in the virtual mine?

17) How well were you able to move and interact within the simulation? Were you limited in any way?

18) What previous experience were you able to draw upon to assist you during the simulation?

19) What things were unknown or uncertain to you during the training scenarios?

20) What things did you need to consider during the training scenarios?

21) What information did you need to know in order to complete the training scenarios successfully?

22) Could you identify any objects or actions that were interrelated during the simulation?

23) How did the level of physical effort required change as you moved through the virtual mine?

24) How did physical effort affect your breathing?

25) How did physical effort affect the rate at which oxygen in your self-rescuer was consumed?

26) How did your existing knowledge of the Challenger mine and its emergency evacuation procedures affect your performance within the simulator?

27) What was you strategy for completing the training scenarios?

28) Which aspects of the training scenarios seemed clear or familiar to you?

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29) What knowledge of the Challenger mine did you posses prior to using the simulator?

30) What knowledge of emergency evacuation procedures did you posses prior to using the simulator?

31) How did you perceive the training scenarios as a result of this pre-existing knowledge?

32) How quickly did you recognise the virtual environment as the Challenger mine?

33) How quickly did you realise that you were in an emergency evacuation scenario?

34) How clear was the relationship between movement speed, physical effort, and oxygen consumption when using the self-rescuer?

35) Were the training scenarios worthwhile and meaningful?

36) What skills did you use to complete the training scenarios?

37) What was the ideal route to take to a refuge chamber during the training scenarios?

38) How well would someone need to know the Challenger mine and its emergency evacuation procedures in order to successfully complete the training scenarios?

39) What motivated you to complete the training scenarios?

40) What information were you aware of at the beginning of each training scenario? How did you acquire this information?

41) How did the simulator respond to your actions? What feedback was provided?

42) Was the feedback information provided by the simulation authentic in relation to the real world mine?

43) Was the manner in which feedback was provided authentic in relation to the real world mine?

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44) To what extent did you feel in control of the learning process?

45) What previous knowledge and experience did you find useful during the training scenarios?

46) Did the simulation guide you towards learning things that were important for emergency evacuations at Challenger?

47) What information did you use to complete the training scenarios?

48) Did the simulation identify important information for you?

49) What new knowledge have you acquired as a result of using the simulation?

50) What aspects of the training scenarios do you think led to the development of new knowledge?

51) What future applications do you think your newly acquired knowledge may have?

52) Which of your senses were provided with information at the beginning of each training scenario?

53) What can you recall about your experience with the simulator?

54) Describe the beginning of each training scenario.

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Appendix 9: Training Staff Member Interview

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Interview Questions

1) Briefly describe your background at Challenger. How long have you worked at Challenger for?

2) Do you have previous experience in underground mining before Challenger? If so, please describe

3) Were you able to observe participants while they used the simulator? Describe your observations.

4) How did participants respond to the simulator overall? Was it received positively or negatively?

5) Did participants have any problems with the simulator?

6) What value would the simulator have for real world emergency evacuation training?

7) How well do you think participants performed using the simulator?

8) Was there any difference in performance between participants who were existing employees at Challenger compared to new employees?

9) Based on your observations, do you think participants were able to use their existing knowledge of the Challenger mine within the simulator?

10) Did the simulation fairly and accurately assess the outcome of each training scenario?

11) Did the simulation reliably assess the outcome of each training scenario?

12) Did the simulation assess the outcome of each training scenario in a manner that was consistent with measures used in the real world mine?

13) Did you provide any assistance to participants while they were using the simulator?

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14) Did the participants answer the reflective questions at the end of the scenarios? Were their answers appropriate? How readily were they able to provide answers?

15) What omissions or features were lacking in the simulator?

16) During an emergency evacuation of the Challenger mine, how would you be able to tell if personnel were familiar with the layout and structure of the mine?

17) Would you expect someone who knew the mine well to take less time and travel a shorter distance to reach a refuge chamber than someone who didn't know the mine well?

18) Would someone who knew the mine well be more likely to go to the ideal refuge chamber and take the ideal route to get there during a given emergency evacuation scenario?

19) Would you expect someone who knew the mine well to be more likely to successfully reach a refuge chamber?

20) How many of the in-experienced guys did you end up helping when they got stuck or lost? What exactly did you do to help them? How many of the inexperienced guys do you think would have never reached a refuge chamber in FUMES without your help when they got lost?

21) How often did people at Challenger do emergency evacuation training drills? What did these drills involve and how effective do you think they were in developing the knowledge and skills needed for real emergency evacuations? Were there any other kinds of drills or training that personnel at Challenger undertook during their course of employment?

22) How experienced were the guys in the expert group? How long had they worked at Challenger for on average?

23) Did you have any particular criteria as to the personnel you selected to use in the FUMES study?

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Appendix 10: Refereed Publications

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McMahon, M. T. J, & Garrett, M. (2011). Exploring the use of audio-visual feedback within 3d virtual environments to provide complex sensory cues for scenario-based learning. *Changing Demands, Changing Directions, Proceedings ascilite Hobart 2011* (pp. 412-422). Hobart, Tasmania: University of Tasmania.

Garrett, M., & McMahon, M. T. J. (2011). The SUPL approach: A conceptual framework for the design of 3d e-simulations based on gaming technology within a problem-based learning pedagogy. In D. Holt, S. Seagrave, J. L. Cybulski (Eds.), *Professional education using e-simulations: Benefits of blended learning design* (1st ed., pp. 233-254). Hershey PA, Business Science Reference.

Garrett, M., & McMahon, M. T. J. (2010). Maximising efficiency of training outcomes using inexpensive 3d technologies. *SIMTECT 2010 Conference Proceedings*. Lindfield, NSW Australia: Simulation Industry Association of Australia.

Garrett, M., & McMahon, M. T. J. (2010). Enhancing the spatial awareness of trainee submariners using 3d game engines as training tools. *International Journal of Intelligent Defence Support Systems (IJIDSS), 3(3/4)*, 151-171.

Garrett, M., & McMahon, M. T. J. (2010). Computer-generated three-dimensional training environments: The simulation, user, and problem-based learning (SUPL) approach. *International Journal of Gaming and Computer-Mediated Simulations, 2(3)*, 43-60.

Garrett, M., & McMahon, M. T. J. (2009). Developing knowledge for real world problem scenarios using 3d gaming technology within a problem-based learning framework. *SIMTECT 2009. Simulation, Concepts, Capability & Technology. Conference Proceedings*. Lindfield, NSW Australia: Simulation Industry Association of Australia.

Garrett, M., & McMahon, M. T. J. (2008). Serious games for defence training: Using the location and scenario training system to enhance the spatial awareness of trainee submariners. *Simtect 2008 Conference Proceedings*. Lindfield, NSW Australia: Simulation Industry Association of Australia.