This article explores the potential learning benefits of three-dimensional (3-D) virtual learning environments (VLEs). Drawing on published research spanning two decades, it identifies a set of unique characteristics of 3-D VLEs, which includes aspects of their representational fidelity and aspects of the learner–computer interactivity they facilitate. A review of applications of 3-D VLEs is presented, leading to the identification of a series of learning affordances of such environments. These affordances include the facilitation of tasks that lead to enhanced spatial knowledge representation, greater opportunities for experiential learning, increased motivation/engagement, improved contextualisation of learning and richer/more effective collaborative learning as compared to tasks made possible by 2-D alternatives. The authors contend that the continued development of and investment in 3-D games, simulations and virtual worlds for educational purposes should be considered contingent on further investigation into the precise relationships between the unique characteristics of 3-D VLEs and their potential learning benefits. To this end, they conclude by proposing an agenda or ‘roadmap’ for future research that encompasses empirical studies aimed at exploring these relationships, as well as those aimed at deriving principles and guidelines to inform the design, development and use of 3-D virtual environments for learning.
What are the learning affordances of 3D virtual environments?

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Abstract
This article explores the potential learning benefits of three-dimensional (3D) virtual learning environments (VLEs). Drawing on published research spanning two decades, it identifies a set of unique characteristics of 3D VLEs, which includes aspects of their representational fidelity and aspects of the learner-computer interactivity they facilitate. A review of applications of 3D VLEs is presented, leading to the identification of a series of learning affordances of such environments. These affordances include the facilitation of tasks that lead to enhanced spatial knowledge representation, greater opportunities for experiential learning, increased motivation/engagement, improved contextualisation of learning and richer/more effective collaborative learning as compared to tasks made possible by 2D alternatives. We contend that the continued development of and investment in 3D games, simulations and virtual worlds for educational purposes should be considered contingent on further investigation into the precise relationships between the unique characteristics of 3D VLEs and their potential learning benefits. To this end, we conclude by proposing an agenda or ‘roadmap’ for future research that encompasses empirical studies aimed at exploring these relationships, as well as those aimed at deriving principles and guidelines to inform the design, development and use of 3D virtual environments for learning.

Introduction
Three-dimensional (3D) technologies have become a fundamental element of almost all modern computer games, including most of the current Massively Multiplayer Online Games (MMOGs) such as World of Warcraft. They are also central to the new generation of immersive virtual worlds, such as Active Worlds and Second Life. Internationally, educators and educational institutions envisage great potential in the use of 3D simulations, games and virtual environments for teaching and learning, as they provide the possibility of rich learner engagement together with the ability to explore, construct and manipulate virtual objects, structures and metaphorical representations of ideas. Much time, financial and other resources are therefore being devoted to efforts aimed at harnessing the pedagogic potential of these technologies, with academia, industry and government working to develop new platforms, tools and resources to support these endeavours (de Freitas, 2006). However, very few empirical studies have been conducted that have documented enhanced post-test knowledge and/or skills of students using desktop-based 3D environments, over those using equivalent 2D technologies. The primary aim of this article is to critically examine the pedagogical benefits of 3D virtual learning environments (3D VLEs), through a review and analysis of a range of potential and actual applications of such environments.
3D virtual learning environments

A 3D virtual environment (3D VE) can be defined as an environment that ‘capitalizes upon natural aspects of human perception by extending visual information in three spatial dimensions’, ‘may supplement this information with other stimuli and temporal changes’ and ‘enables the user to interact with the displayed data’ (Wann & Mon-Williams, 1996, p. 833). Three-dimensionality, smooth temporal changes and interactivity are the most important features that distinguish 3D VLEs from other types of VLEs, such as those provided by a Learning Management System (LMS) like Blackboard or Moodle. The present article is primarily concerned with 3D VLEs that can be explored using standard personal computer (PC) hardware commonly available in schools and homes, often termed ‘desktop virtual environments’, although the discussion may also apply to ‘immersive virtual environments’ such as those requiring the use of specialised hardware like head-mounted displays (HMDs), multi-wall CAVE automatic virtual environment (CAVE) systems, high-degree of freedom input devices and video tracking systems.

In his literature review on 3D virtual and game environments, Jacobson (2006) cites several studies conducted since the mid-1990s whose results suggest that immersive 3D VLEs, if appropriately designed and used, may provide ‘value-added’ learning over 2D technologies used to deliver equivalent educational content. However, the costs associated with the equipment and computational power required for these applications have made them largely prohibitive in mainstream settings. Thus, the findings of these studies have had little practical impact to date in spite of their theoretical significance. In recent years, the ubiquity of multimedia and Internet-capable PCs has led to a resurgence of interest in Web-based virtual reality (VR). The highly interactive and multi-player engagement afforded by commercially available 3D games has attracted millions of users worldwide to use these technologies, and given rise to a sizeable economic market that continues to fuel further research and development in this area. It is therefore not surprising that large numbers of educators across the globe are attempting to harness the educational power of these technologies, excited at the prospect of ‘co-opting’ (Buchanan, 2003) the tools and toys students already use for communication and entertainment to help them learn better. Commercial, off-the-shelf (COTS) 3D games are being repurposed and adapted for use in classrooms (Gikas & Van Eck, 2004; Van Eck, 2006; Sandford, 2006), while new, educational games and virtual environments are being developed to address specific curricular content (see for example, Barab, Thomas, Dodge, Carteaux & Tuzun, 2005; Squire, Barnett, Grant & Higginbotham, 2004; Jacobson, Kim, Lee, Lim & Low, 2008).

Nevertheless, amidst the current hype surrounding desktop 3D technologies, a critical look at the research to date suggests that the case for how these technologies support learning remains equivocal, with the learning outcomes achieved in projects in this area being discussed in very generic terms (Jacobson, 2006). Though a number of researchers (for example, Gee, 2003; Steinkuehler, 2004) have documented educationally-relevant outcomes, there is little conclusive evidence that attests to the specific learning benefits of 3D VLEs, that is benefits that emanate particularly from the three-dimensional aspects of these environments (McFarlane, Sparrowhawk & Heald, 2002; McLellan, 2004). This article seeks to isolate the distinguishing characteristics of 3D VLEs and the potential benefits that may accrue from the learning tasks they afford, based on a systematic analysis of research literature and project reports in this area. Later in the article, the derivation of a list of affordances of 3D VLEs for learning will serve as a platform for a proposed research agenda (an affordance of a tool is essentially an action made possible by the availability of that tool). This agenda will help to establish a sound theoretical base to support the work of both researchers and practitioners interested in the use of 3D games, simulations and virtual worlds for learning.

Distinguishing characteristics of 3D virtual environments

3D VLEs exhibit a unique set of characteristics from a pedagogical point of view. Hedberg and Alexander (1994) suggest that their most important defining feature is the ‘transparent interface with which the user directly controls the objects in the context of the virtual world’ (p. 215). In identifying the features of virtual environments that make them distinct from interactive multimedia, they name three aspects of virtual environments that contribute to this transparency and through which such environments have ‘the potential to offer a superior learning experience’ (p. 218): increased ‘immersion’, increased ‘fidelity’ and a higher level of ‘active learner participation’.

There is some agreement between Hedberg and Alexander’s ideas and those of Whitelock, Brna and Holland (1996), who propose a theoretical framework in order to explore the relationship between virtual environments and conceptual learning. Their framework, which extends the work of Zeltzer
(1992), includes the identification of three properties or dimensions of 3D VLEs, namely ‘representational fidelity’, ‘immediacy of control’ and ‘presence’. ‘Fidelity’ appears as a factor in both Hedberg and Alexander’s and Whiteberg et al.’s models, and Whitelock et al.’s ‘immediacy of control’ relates very closely to Hedberg and Alexander’s ‘active learner participation’. Hedberg and Alexander use the term ‘immersion’ to encompass both the physical aspects of the environment and the psychological sense of being in the environment, while Whitelock et al. use ‘presence’ in a similar way, that is to include both the objective characteristics of the environment and the user’s subjective experience. Consequently, Hedberg and Alexander’s property of immersion can be equated with Whitelock et al.’s presence dimension.

Both Hedberg and Alexander and Whitelock et al. focus on the characteristics of single-user virtual environments, that is, they are concerned primarily with the way in which an individual interacts with such an environment on his/her own. Brna (1999), on the other hand, extends his earlier work with Whitelock and Holland (ie, Whitelock et al., 1996), to propose a framework that incorporates the social factors involved in the use of multi-user virtual environments (MUVEs). His six-dimensional framework includes Whitelock et al.’s ‘representational fidelity’, ‘immediacy of control’ and ‘presence’, as well as three additional elements: ‘social fidelity’ (including social familiarity and social reality), ‘immediacy of discourse’ and ‘social presence’.

Many authors have stressed the importance of immersion and presence, suggesting that these are critical features distinguishing virtual environments from other types of computer applications (McLellan, 2004; Mikropoulos & Strouboulis, 2004; Mikropoulos, 2006). In early writings about virtual environments, there was a tendency to use these terms interchangeably; subsequently, debates occurred in the literature about the definitions of these terms (see for example, Witmer & Singer, 1998; Slater, 1999). We concur with Slater (1999, 2003, 2004), who defines presence as the subjective sense of being in a place, and immersion as the objective and measurable properties of the system or environment that lead to a sense of presence. In other words, immersion relies on the technical capabilities of VR technology to render sensory stimuli, whereas presence is context-dependent and draws on the individual’s subjective psychological response to VR. The latter is dependent on a range of factors including but not limited to the user’s state of mind (Slater, 2003).

In looking more closely at the immersive properties of an environment, we argue that it is essentially the fidelity of the representation along with the types of interactivity that are available within the environment that will lead to a high degree of immersion and consequently a strong sense of presence. For this reason, we do not believe that immersion is a unique property. The dependency of immersion on other aspects of the environment is noted by Hedberg and Alexander (1994), who maintain that ‘the interaction of representational fidelity with sensory, conceptual and motivational immersion needs to be examined to determine the complexity of sensory input necessary to establish the learning outcome’ (p. 217). Similarly, we do not believe that presence is a unique property because it occurs as a result of the fidelity and the interactive capabilities of the environment.

While sense of presence in a virtual world or environment has traditionally been used to refer to a user’s perception of ‘being there’ (Ellis, 1995; Schroeder, 2002), a more recent area of research entails the examination of co-presence, defined as the sense of ‘being there together’ with other geographically-dispersed users. The concept of co-presence is considered by many to be an extension of social presence, which emerged as a topic of interest within the field of human-computer interaction in the 1970s (Short, Williams & Christie, 1976) and which was included in Brna’s aforementioned framework (see also Garau, 2003; Biocca, Harms & Burgoon, 2003). It is arguable that many 3D MUVEs support high levels of co-presence, due to the fidelity or realism of the environments within which the shared sensory experiences occur and the facilities available for spatial and other forms of non-verbal communication. Hence, like sense of presence, co-presence may be said to be a result of the various characteristics of the environment rather than being a characteristic of virtual environments as such.

An important aspect of the use of a 3D virtual environment is the way in which users, through their embodied actions and social interactions within the environment, construct online identities for themselves. In many 3D VEs, each user is depicted by an ‘avatar’ that provides a visual representation of his/her real or surrogate identity and appearance. The sense that the avatar he/she is controlling is a portrayal of him/herself (or of an alternative self) that he/she consciously or unconsciously creates within the environment is important both for supporting a rich sense of psychological immersion in the
performance of tasks, as well as for deep levels of communication, collaboration and relationship building (de Freitas, 2006, 2008). Riva (1999) examines the psycho-social issues involved in communication and action in virtual environments, and identifies the relationship between embodiment and presence as an important issue, along with the relationship between identity construction, projection and perception. Dickey (2002) identifies three aspects of the user’s experience that contribute to identity construction: presence (including both the physical state of presence as well as the social impression one makes), representation (including the visual appearance of the person’s avatar, along with their identifying name or description) and embodiment (including their physical actions along with the social positioning of these actions). Importantly, although the ability for the user to construct and portray an identity within the environment is important, we take the view that rather than this being a unique characteristic of 3D VLEs, it is, like presence and co-presence, a consequence of the representational fidelity and learner interactions facilitated by the environment.

Adopting the perspective that representational fidelity and learner interaction are unique characteristics of 3D VLE, whereas construction of identity, sense of presence and co-presence are characteristics of the learner’s experience as a result of these environment characteristics, Figure 1 depicts an initial model of learning in 3D VLEs. In this model, representational fidelity should be taken to incorporate aspects of both single-user and multi-user environments and to incorporate Brna’s concept of social fidelity. Similarly, learner interaction should be taken to incorporate individual, collaborative and communicative actions and consequently to incorporate Brna’s concept of immediacy of discourse.

The two broad categories of representational fidelity and learner interaction can be further elaborated on to identify the specific aspects of 3D learning environments that distinguish such environments from other interactive learning resources (Table 1). The two most important visual aspects of the representational fidelity of a 3D environment are realistic display of the environment and smooth display of view changes and object motion. The display of objects using realistic perspective and occlusion, as well as realistic texture and lighting allows for realism that can approach photographic quality if the 3D model is defined with sufficient detail. However, even when the images do not approach photographic quality, with sufficient frame rates, the image changes that reflect the viewer’s motion or the motion of objects can appear smooth enough to provide a very realistic experience. Another aspect of the fidelity of the representation is the consistency of object behaviours, including the way that they respond to user actions and their autonomous (or modelled) behaviours.
A fourth aspect of representational fidelity is user representation, that is, depiction of the user as an avatar, through which the user is able, according to Dickey (2002), to develop and project an online identity. Benford, Bowers, Fahlén, Greenhalgh and Snowdon (1995) illustrate the complexity of user representation in 3D VE, deriving a list of characteristics to be considered in user representation design. This depiction of users is an important element of the fidelity of the representation because it helps create a sense of co-presence in the environment, which in turn enriches the social interactions occurring (Schroeder & Axelsson, 2006).

Traditionally, applied research on 3D VE focussed primarily on the visual aspects of the representation, with research on environments incorporating other sensory information confined to high-end laboratory systems. More recently, the availability of ‘3D audio’ technologies (Adler, 1996) that provide spatial perception of sounds has become almost ubiquitous in mainstream 3D VE applications (Bowman, Kruijff, LaViola & Poupyrev, 2004); these technologies can be used to direct the user’s attention and enhance the realism of the virtual experience by providing various directional and distance cueing effects (Bormann, 2005). Haptics technologies that allow users to feel force and pressure while interacting with the environment are also becoming commonplace (Bowman et al.), particularly as a feature of many popular videogame consoles. For some years, haptics have been employed as a learning tool for motor skill development in fields such as surgical training (Gunn, Hutchins, Stevenson, Adcock & Youngblood, 2005; Ström et al., 2006), in which it is used to reproduce an expert’s skill in the form of tactile and kinaesthetic perceptions using the expert’s temporal position, velocity and force information; they are now also being applied to the learning of abstract concepts in 3D VLEs (Harvey & Gingold, 2000; Jones et al., 2004; Minogue, Jones, Broadwell & Oppewall, 2006). Consequently, it is now reasonable to include kinaesthetic and tactile force feedback along with spatial audio as characteristics of the representational fidelity of the environment.

In relation to learner interaction, an important aspect that is unique to 3D environments is the ability to undertake embodied actions, including view control, navigation and object manipulation. Dall’Alba and Barnacle (2005) have argued that traditional (ie, Web-based) online learning environments tend to be designed to facilitate disembodied ways of learning and knowing, which is at odds with contemporary epistemological theories that emphasise contextual, embodied knowledge. 3D VE have the potential to address this through user representation (discussed above) and embodied action. Dickey (2002) also asserts that embodiment is an important element in the construction and portrayal of an online identity.

Looking specifically at 3D environments with multi-user capabilities, these environments provide the facility for users, through their avatars, to engage in embodied verbal communication through text and voice, as well as embodied non-verbal communication in the form of gestures and facial expressions. Though verbal communication per se is not unique to 3D environments, the embodiment afforded by 3D MUVE provides the added ability to align gesture and actions with written and/or spoken words. An additional interactive characteristic is the way in which the learner can be given control over the attributes and behaviour of the environment, including, for example, the modification of time and gravity parameters. Last but not least, much recent attention has been given to the learning benefits that may arise from enabling learners to construct their own virtual places and/or objects (see for example, Antonacci & Modress, 2008; Boulos, Hetherington & Wheeler, 2007), by capitalising on the extensibility of 3D virtual world and gaming platforms and the ability for the user to undertake ‘modding’ (Hedberg & Brudvik, 2008) and scripting of object behaviours. Table 1 brings together these four aspects of learner interactivity, along with the six aspects of representational fidelity identified above, as a set of ten distinguishing characteristics of 3D VLEs.

The learning affordances of 3D virtual environments
Having identified the unique characteristics of 3D VLEs, we will now attempt to identify a set of contributions to learning potentially arising from tasks afforded by such environments. The term ‘affordance’ was first coined by Gibson (1979), who used it to refer to the functional properties that determine the possible utility of an object or environment (cited in Salomon, 1993). According to Greeno (1994), ‘an affordance relates attributes of something in the environment to an interactive activity by an agent who has some ability’ (p. 338). A number of authors have also used ‘affordance’ in educational contexts to describe the relationships between the properties of an educational intervention and the characteristics of the learner that enable certain kinds of learning to occur (Kirschner, 2002), while others stress the importance of analysing how the affordances of ICTs can be used to facilitate
particular approaches to teaching and learning (see for example, Conole & Dyke, 2004). Bower (2008) proposes a methodology for matching the affordance requirements of learning tasks with the technological affordances of ICT tools, which can be used to help guide and inform the processes of technology selection and learning design. We concur with Bower’s implicit conception of affordances, while acknowledging that the technologies themselves do not directly cause learning to occur but can afford certain learning tasks which themselves may result in learning or give rise to certain learning benefits.

Table 1: Distinguishing characteristics of 3D VLEs

<table>
<thead>
<tr>
<th>Category</th>
<th>Characteristic</th>
</tr>
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<tbody>
<tr>
<td>Representational fidelity</td>
<td>Realistic display of environment</td>
</tr>
<tr>
<td></td>
<td>Smooth display of view changes and object motion</td>
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<tr>
<td></td>
<td>Consistency of object behaviour</td>
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<tr>
<td></td>
<td>User representation</td>
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<tr>
<td></td>
<td>Spatial audio</td>
</tr>
<tr>
<td></td>
<td>Kinaesthetic and tactile force feedback</td>
</tr>
<tr>
<td>Learner interaction</td>
<td>Embodied actions including view control, navigation and object manipulation</td>
</tr>
<tr>
<td></td>
<td>Embodied verbal and non-verbal communication</td>
</tr>
<tr>
<td></td>
<td>Control of environment attributes and behaviour</td>
</tr>
<tr>
<td></td>
<td>Construction of objects and scripting of object behaviours</td>
</tr>
</tbody>
</table>

In this section, a range of proposed and actual applications of 3D VEs for learning are reviewed, leading to the identification of five learning affordances of such environments. These affordances represent the theoretical learning benefits of 3D VLEs explicitly and/or implicitly purported by authors in the literature; our choice of the term ‘affordances’ in preference over ‘benefits’ or ‘advantages’ is in recognition of the aforementioned view that it is the tasks, activities and underpinning pedagogical strategies supported or facilitated by the technology rather than the technology itself that have an impact on learning; additionally, the use of a particular technology or media form does not guarantee the yield of specific learning outcomes or benefits (see Clark, 1983, 1994a, b).

The applications reviewed have been grouped into three broad categories: 3D simulations and microworlds, 3D environments as interfaces to learning resources and 3D multi-user VLEs. It is important to note that these categories have been used only to help structure the review—We recognise that they are not mutually exclusive, as a particular resource could fit into more than one category.

3D simulations and microworlds

Simulations have been used as part of computer-assisted learning (CAL) materials for at least three decades, with SimCity (Wright, 1989) being one of the earliest and most popular examples. Simulated 3D environments modelled on real places and objects have the potential to provide an enhanced sense of realism and a greater sense of presence as compared to non-3D environments. Their fidelity is such that where barriers exist to visiting the real place, immersion in the 3D VE can be a viable alternative. For example, Alberti, Marini and Trapani (1998) describe a 3D VE modelled on a historic theatre in Italy, while Kontogeorgiou, Bellou and Mikropoulos (2008) describe the exploration of 3D simulated microscopic environments in an effort to allow students to experience being inside a quantum atom. In Virtual Big Beef Creek (Campbell, Collins, Hadaway, Hedley & StoeRner, 2002), a 3D VE that recreates a marine and coastal environment to assist in the teaching of Ocean Science, learners can assume the roles of scientists to collect and analyse geo-scientific data, or alternatively, take on characters representing creatures that inhabit the environment, which are variously able to walk over land, swim underwater or fly across the sky. In this way, the learners are able to explore firsthand the abilities and limitations of the various animals, while simultaneously acquiring knowledge about the flora, fauna, ecosystem and ocean environment at large.
The ability to move freely around the 3D VLE, view it from any position and manipulate objects within it has the potential to assist in the development of spatial knowledge of the real environment beyond that which is possible through non 3D alternatives, including those using photographic or video material or panoramic photographic technologies (eg, QuickTime VR [Apple, 2008]). This leads to the first learning affordance of 3D VLEs:

**Affordance 1.** 3D VLEs can be used to facilitate learning tasks that lead to the development of enhanced spatial knowledge representation of the explored domain.

One of the most important potential benefits of simulations occurs through the learner interacting with objects in the virtual environment. Any knowledge domain in which the learner is expected to develop an understanding of entities exhibiting dynamic behaviours may be suited to simulations where he/she is able to construct a personal knowledge representation and iteratively refine this representation as he/she undertakes exploration and experimentation, in a manner consistent with cognitive constructivist learning theories (Piaget, 1973; Jonassen, 1991). For example, physics students are expected to understand how objects will respond to forces; exploring an environment that allows for specific forces to be applied to objects and for the resultant object behaviours to be observed and measured may assist in improving their conceptual understanding (Chee & Hooi, 2002). 3D technologies are well suited to such physical simulations because they enable the full physical behaviour of objects to be modelled, rather than restricting the motion and behaviour to two dimensions. Learning benefits over 2D simulations will occur if the use of a 3D VE like this leads to a 3D conceptual model of the physical concepts rather than a simplified 2D conceptual model, and/or if learners stand to gain from viewing an object or setting from more than one vantage point (Bricken 1990; Dede, Salzman & Loftin, 1996). Again, then, the spatial knowledge representation afforded by 3D VEs provides the potential for learning benefits.

Simulations can also allow learners to practise skills or undertake embodied learning tasks, and this is particularly appropriate when the tasks involved are expensive, dangerous or risky to undertake in the real world. For example, 3D VE-based simulations have been used to train nuclear power plant workers in Japan (Akiyoshi, Miwa & Nishida, 1996, as cited in Winn & Jackson, 1999), to train astronauts in how to repair a space telescope (Psotka, 1995; Moore, 1995) and to train forestry machine operators (Lapointe & Robert, 2000). Chen and Toh (2005) describe a driver education resource containing interactive 3D simulations of driver education scenarios; and John (2007) surveys a range of Web3D-based tools that have been designed to support training for a variety of medical procedures. This leads to the second affordance of 3D VLEs:

**Affordance 2.** 3D VLEs can be used to facilitate experiential learning tasks that would be impractical or impossible to undertake in the real world.

In some knowledge domains, the concepts to be learnt are abstract and do not correspond directly to material objects. The term ‘microworld’ is often used to describe simulations of abstract environments designed for concept formation (Rieber, 1992). Winn and Jackson (1999) suggest that virtual environments are ‘most useful when they embody concepts and principles that are not normally accessible to the senses’ (p. 7). They use the term ‘reification’ to describe the representation of phenomena that have no natural form. For example, they describe an environment that allows learners to control greenhouse gas emissions and to view models that metaphorically represent the effects of global climate change. Ruzic (1999) also notes the potential for the use of metaphorical entities within virtual environments, suggesting that such environments incorporate two types of objects, ‘tangible (sensory) objects called sensory transducers, and intangible, cognitive objects called cognitive transducers’ (p. 189).

Other examples of 3D microworlds for learning are portrayed by Kaufmann, Schmalstieg and Wagner (2000) and Yeh and Nason (2004), who describe 3D environments for developing learners’ understanding of geometry; Bares, Zettlemoyer and Lester (1998), who describe a CPU City microworld used in the teaching of computer science; and Salzman, Dede, Loftin and Chen (1999), who describe three immersive environments that provide abstract spatial representations allowing learners to explore Newtonian mechanics, electrostatic forces and molecular bonding. The simulated radioactivity laboratory described by Crosier, Cobb and Wilson (2000) allows learners to carry out tasks and measure the results at the laboratory level and then to zoom in and visualise what is happening at the atomic level. Furthermore, 3D microworlds may be used to allow the learner to
construct his/her own 3D environment as a way of articulating his/her spatial model or ‘externalising’ his/her understanding of particular abstract concepts (Winn, 2002). A number of 3D concept mapping tools have been developed for such purposes, examples of which are Nelements (AYAR Software, 2007) and Topicscape (3D-Scape, 2008).

The above examples of 3D microworlds and abstract simulations have in common the way in which they help the learner to understand the concepts within the target domain by capitalising on the first affordance of 3D VLEs mentioned above, namely their ability to support learning tasks leading to the formation of spatial knowledge representations.

Another potential learning benefit of simulations and microworlds is that they can be intrinsically motivating and engaging due to the high degree of personalisation as the learner makes choices in attempting to achieve individual goals within the environment (Rieber, 2005; Cordova & Lepper, 1996). Game and narrative-based approaches, when used in conjunction with 3D VEs, can also contribute to learner motivation and engagement (Garris, Ahlers & Driskell, 2002; Mitchell & Savill-Smith, 2005). According to Csikszentmihalyi (1990), some activities can be so engaging that our mental focus is shifted away from our surroundings and from the day-to-day stresses in our lives, allowing us to focus entirely on the task. He uses the term ‘flow’ to describe the learner’s experience in these situations. The high degree of fidelity and the natural interface of 3D VEs may increase the likelihood that the learner will experience this feeling of flow as they become psychologically immersed within the environment. This illustrates, then, the third learning affordance of 3D VEs:

Affordance 3. 3D VLEs can be used to facilitate learning tasks that lead to increased intrinsic motivation and engagement.

3D environments as interfaces to learning resources
A number of studies have found that learners can have difficulty navigating hypermedia environments, with the problems characterised by the ‘lost in hyperspace’ phenomenon (MacKnight, Dillon & Richardson, 1991) whereby users lose track of how they arrived at a node and have no clear model of the overall environment structure. The provision of an interface that allows easy navigation through the information, while maintaining a sense for the overall structure of the resources and the connections between ideas, is problematic. 3D environments offer transparency of knowledge representation, which allows learners to approach concepts as ‘first-person, non-symbolic’ experiences, unlike most instances in which information is codified and represented as ‘third-person, symbolic’ experiences (Winn, 1993, cited in Dickey, 2005a). These applications attempt to capitalise on learners’ well-developed spatial cognitive abilities to assist them in navigating within the information space (Liang & Sedig, 2009).

Card, Robertson and York’s (1996) description of the use of a 3D environment as an interface for navigating through a complex information space and Robertson et al.’s (2000) description of the use of a 3D interface for task management on a PC are consistent with this idea. These applications provide further examples of the first affordance mentioned above, that is the ability of 3D VLEs to facilitate learning tasks leading to spatial knowledge representation. The formation of a spatial cognitive model of the information space as a result of exploring an environment has the potential to boost exploration efficiency and conceptual understanding of the learning domain.

It can also be argued that there will be more effective real-world application of newly-acquired knowledge and skills if the learning environment is modelled on the context in which the knowledge is expected to be applied. Specifically, because 3D technologies can provide levels of visual or sensory realism and interactivity consistent with the real world, ideas learnt within a 3D VE should be more readily recalled and applied within the corresponding real environment. This is a logical corollary to the idea that knowledge can be internally anchored to experience. Research carried out by Baddeley (1993) supports this idea by suggesting that facts learnt by divers under water are better recalled while diving than facts learnt on land. Ruzic (1999) emphasises the situated nature of learning in virtual environments, and consequently the potential for application within similar real environments, stating that ‘the advantages of VR-based teleteaching are individualised, interactive and realistic learning that makes virtual reality a tool for apprenticeship training, providing a unique opportunity for situated learning’ (p. 188). Many other authors (for example, McLellan, 2004; Bronack, Riedl & Tashner, 2005; Chittaro & Ranon, 2007) have similarly noted the potential for 3D VLEs to situate learning, drawing on the theoretical foundations laid down by Lave and Wenger (1991) and Brown, Collins and Duguid (1989).
This leads to the fourth affordance:

**Affordance 4.** 3D VLEs can be used to facilitate learning tasks that lead to improved transfer of knowledge and skills to real situations through contextualisation of learning.

**3D multi-user virtual learning environments**

Dede (1995) discussed the possibility of combining the capabilities of virtual environments with the capabilities of Computer Mediated Communication (CMC) tools to promote collaborative learning within a distributed virtual environment. Today’s multi-user, distributed 3D environments, including MMOGs and virtual worlds, allow geographically-dispersed users to explore an environment concurrently, with each represented by a surrogate persona or avatar visible to other users, and with tools allowing text-based or audio communication. At a simple level, such environments can provide a vehicle for remote support by a teacher or facilitator as a learner undertakes learning tasks, however they also have great potential as social learning and Computer Supported Collaborative Learning (CSCL) tools (Edirisingha, Nie, Pluciennik & Young, 2009). According to social constructivist views of learning, conversation and discourse are the cornerstones of collaboration and social negotiation in learning (Lave & Wenger, 1991; Vygotsky, 1978; Jonassen, 1999). Communication within a simulated environment relevant to the ideas being discussed can provide a greater ‘sense of place’ than other text-based alternatives such as instant messaging, chat rooms and multi-user dungeons/dimensions (MUDs), and consequently help foster greater closeness within the group and richer communication due to the ability to draw on spatial and non-verbal cues. If role-play strategies are used, it is likely that learners will more easily ‘lose themselves’ as they adopt their role and identify with their avatar, due to the fidelity of the environment. This ability to self-define and take on alternate personae gives learners opportunities to adopt multiple perspectives, the importance of which is a key tenet of constructivist learning (Jonassen, 1991, 1994; Honebein, 1996), while the willed suspension of disbelief and emotional realism encourage them to engage in exploration, inquiry and risk taking (Dickey, 2005b).

Most importantly, multi-user 3D environments can allow learners to undertake tasks together rather than just communicate. It is widely acknowledged that cooperative and collaborative learning strategies should involve activities and tasks that entail positive interdependence between participants, that is, require that each group member’s efforts be indispensable for the success of the group in achieving its goals, and that each member make a unique and valued contribution through his/her resources and/or role and task responsibilities (Johnson, Johnson and Holubec, 1993; Johnson & Johnson 1994). 3D VEs that allow learners to engage simultaneously in shared tasks and/or produce joint artefacts by operating on the same objects in real time can pave the way for rich and truly collaborative experiences that foster positive interdependence within a learning group. For example, Mennecke, Hassall and Triplett (2008) report on how students undertake a scavenger hunt activity in Second Life (SL), in which they co-experience and explore the virtual world as they embark on a mission to discover interesting places and practise basic SL skills. To complete the exercise, they must retrieve the relevant instructions, decipher the embedded hints and ‘teleport’ to the location of the item they are searching for. The activity requires students to work in teams, communicating and coordinating their activities and collaborating in the process. Successful completion is achieved when the team leader submits a note card containing details of the team’s collaboration as outlined in the scavenger hunt instructions.

In another example, Jarmon, Traphagan and Mayrath (2008) describe how students in a graduate interdisciplinary communication course work together and in collaboration with architecture students at the same university to create a virtual presence in SL of two green, sustainable, urban housing designs that are later physically implemented in a low-income neighbourhood in Austin, Texas. Successfully completing the course assignments and projects calls for the students to interact extensively with educational and non-academic participants both in real life and in the 3D virtual world. Positive interdependence is also evident in that the communication students require the domain knowledge and expertise of the architects, and vice versa.

These examples demonstrate the fifth learning affordance of 3D virtual environments:

**Affordance 5.** 3D VLEs can be used to facilitate tasks that lead to richer and/or more effective collaborative learning than is possible with 2D alternatives.
A model of learning in 3D virtual learning environments
Taking the results of the above analysis along with the ten distinguishing characteristics of 3D VLEs identified earlier in the article allows the initial model shown in Figure 1 to be used as the basis of the detailed model of learning in 3D VLEs illustrated in Figure 2. This model presents an overall or big-picture snapshot of what authors are claiming/asserting and implying about 3D VLEs, their characteristics and potential learning benefits, much of which calls for further investigation. It has the potential to contribute to the conceptualisation of a research agenda for learning in 3D virtual environments; the next section presents a preliminary outline or ‘skeleton’ of such an agenda.

![Figure 2: Elaborated model of learning in 3-D VLEs, incorporating unique characteristics and learning affordances](image)

Towards a research agenda: conclusion and recommendations
This article has highlighted the unique characteristics of 3D virtual learning environments, as well as the potential learning benefits that stem from their affordances, based on an examination of applications described in the literature. Much that has been published about the educational uses of 3D technologies is largely ‘show-and-tell’, presenting only anecdotal evidence or personal impressions that cannot be usefully generalised beyond the local context. The continually increasing amount of time and resources being allocated to the development of 3D games and virtual worlds by institutions and education systems worldwide, on the premise of improved learning outcomes, calls for a concerted and systematic effort by researchers to ascertain whether or not, and if so, how, the capabilities and features of 3D VLEs can be exploited in pedagogically sound ways. Surprisingly little is known about the cognitive value of desktop 3D graphics and virtual reality (Chen, 2006; Lee & Wong, 2008), notwithstanding the fact that the core technologies supporting these innovations are not new, and have
seen many uses not only in education, but also in diverse areas of commerce, industry, entertainment and the military since the genesis of the multimedia PC in the early 1990s.

To move ahead, the model of learning in 3D VLEs derived in this article (Figure 2) may be used as a basis for defining an agenda for research into the design and use of such environments. First and foremost, future research needs to include empirical studies to establish the validity of the assumptions about 3D VLEs that are implicit within the design of these environments and the associated learning tasks. Many claims that have been made about the benefits of 3D virtual environments for education are couched in a long line of assumptions about technological advancements in computer graphics and multimedia, each asserting progressively better ways of facilitating cognitive tasks that seem sensible and obvious at face value (Scaife & Rogers, 1996). It is arguable that the degree to which 3D VLEs have the potential to provide learning advantages over non-3D resources, in particular, is dependent on a number of underlying, general assumptions about cognition and learning in 3D environments, along with assumptions about links or connections between the distinguishing characteristics of 3D VLEs and the potential or anticipated learning benefits shown in Figure 2.

For instance, a general assumption that needs empirical exploration is the supposition that learners will trust their virtual environment-based experiences sufficiently to modify their mental models of the simulated concepts, thereby correcting any misconceptions held. An example of an assumption about the connections between characteristics of 3D VLEs and their learning benefits may be seen in the notion that when factual information is learnt within a 3D VLE, there will be greater transfer of learning to the corresponding real environment. This notion hinges on an additional assumption, namely the intuition that the greater fidelity of a 3D VLE leads to a greater sense of presence, and consequently, greater transfer. A second example is the idea that the interactivity provided by 3D VLEs will result in greater spatial learning than would occur when passively viewing an equivalent animation or video; a third is the assumption that a 3D MUVE’s representational fidelity and the embodied actions it facilitates will result in richer online identity construction and a greater sense of co-presence, and that this in turn will bring about more effective collaborative learning.

In discussing the need for empirical exploration of the validity of the assumptions implicit within the design of 3D VLEs, it is important to point out that we are not advocating studies that compare the learning benefits of equivalent 2D and 3D environments using contrived examples in inauthentic settings. Clark (1983, 1994a, b) has argued coherently against studies that look for a direct connection between a particular learning media or technology and learning, on the basis that in such studies it is not possible to separate the learning design from the media. We have argued in this article that 3D VLEs afford certain learning tasks, or in other words, well-designed 3D VLEs can enable learning tasks that are not possible or not as effective in 2D environments. Comparisons between 2D and 3D environments that control the learning design across environments would be likely to only demonstrate the trivial fact that if the unique affordances of 3D VLEs are not harnessed within the learning design, there will be minimal unique learning benefits.

Finally, realising the promise of 3D VLEs to deliver enhanced learning and educational benefits necessitates applied research that derives design principles that will in turn inform the development of best practice. Such work is contingent on fulfilling the aforementioned need for empirical studies to establish the validity or otherwise of the basic assumptions about 3D VLEs, and to link the unique characteristics of 3D VLEs with the potential learning benefits. Currently, design and development efforts in this field are largely hit-and-miss, driven by intuition and ‘common-sense’ extrapolations rather than being solidly underpinned by research-informed models and frameworks. More work is needed to bring the virtual world / games development and education communities closer together (de Freitas, 2006), and researchers and practitioners must make time for awareness raising, dialogue and discussion about what works and why, and which combinations of pedagogic strategies and tools best target the desired outcomes. Teachers and learners require time for up-skilling and development, as well as guidance on how to plan and implement appropriate activities to use in conjunction with 3D VLEs, including both those that are endogenous and exogenous to the virtual environment or world.

Table 2 summarises the proposed agenda and, by way of illustration, lists some of the many possible research questions to be addressed and hypotheses to be tested within each of the three aforementioned categories. It is worth noting that there is already an ongoing stream of research that attempts to address some of these questions; however, a more unified effort is needed to accurately target, validate and take advantage of the capabilities and features of 3D virtual environments for learning, working
from the ground up. Once the fundamental questions have been properly addressed, developers of 3D VLEs and educators wishing to make use of these tools in their classrooms will have a firm basis for their design decisions. Even more importantly, when more is known about the aspects of such environments that are critical for learning, there will be a much greater likelihood that sound instructional design and pedagogy will prevail over the mere novelty of the technology. It is only then that the resources developed can truly move beyond simply impressing the learner with technological ‘niftiness’ or visual realism to actually facilitate effective learning.

**Table 2: A roadmap for further research into 3D VLEs**

<table>
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<tr>
<th>Study type</th>
<th>Overarching goal/rationale</th>
<th>Examples of research questions to be addressed</th>
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| 1. Testing basic assumptions and linking characteristics to affordances | Return to ‘first principles’ by validating or refuting the basic, underlying assumptions implicit in the design and use of 3D VLEs, and in particular determining and defining the relationships between the unique characteristics of 3D VLEs, the intermediate outcomes (identity, presence, co-presence) and the anticipated learning benefits that arise from the tasks afforded by these environments. | • Will learners trust experiences in a 3D VLE sufficiently to modify any misconceptions held?  
• Do realistic display, smooth view changes and embodied actions each contribute independently or together to spatial knowledge development, when compared to alternative static or animated images?  
• How important are the various aspects of the environment fidelity, such as visual realism and refresh rate, to the achievement of a sense of presence in a 3D VLE?  
• Do the use of spatial audio and tactile feedback lead to the achievement of a greater sense of presence in a 3D VLE?  
• Do the greater fidelity and sense of presence within a 3D VLE lead to greater engagement and intrinsic motivation?  
• Do the greater fidelity and sense of presence within a 3D VLE lead to improved contextualisation of learning, manifested through greater transfer to a corresponding real environment?  
• How do the use of and fidelity of spatial audio and tactile feedback in 3D VLEs contribute to the learner’s development of spatial knowledge representations?  
• Does the facilitation of embodied actions and communication within a 3D MUVE lead to a greater sense of co-presence? Does this, in turn, afford learning tasks that encourage richer and/or more effective collaborative learning than is possible with 2D alternatives? |
| 2. Establishing guidelines and best practice | Identify/derive rules and principles that will guide and inform the design and development of 3D VLEs and associated learning tasks. | • What changes to accepted design principles from established theories (e.g. cognitive load theory, dual coding theory, cognitive theory of multimedia learning), if any, are needed when instructional elements are presented within a 3D VLE?  
• How can learning tasks to be carried out within a 3D VLE be designed to meet specific, desired educational outcomes (e.g. content knowledge in particular subject domains, generic skills such as teamwork and problem solving)?  
• What are the essential characteristics of learning tasks within a 3D VLE that will make such tasks intrinsically motivating?  
• What are the essential characteristics of learning tasks within a 3D VLE that will result in a high sense of presence? How important is suspension of disbelief to the achievement of both cognitive and affective learning goals?]|

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