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The Immersive Virtual Environment of the digital fulldome: Considerations of relevant psychological processes

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Abstract

One of the most recent additions to the range of Immersive Virtual Environments has been the digital fulldome. However, not much empirical research has been conducted to explore its potential and benefits over other types of presentation formats. In this review we provide a framework within which to examine the properties of fulldome environments and compare them to those of other existing immersive digital environments. We review the state-of-the-art of virtual reality technology, and then survey core areas of psychology relevant to experiences in the fulldome, including visual perception, attention, memory, social factors and individual differences. Building on the existing research within these domains, we propose potential directions for empirical investigation that highlight the great potential of the fulldome in teaching, learning and research.

Keywords: Digital fulldome; Immersive Virtual Environment; Virtual reality; Presence; Immersion; Psychology; Learning

0. Introduction

The potential use of modern technology as an educational and research tool has received attention across many areas; Immersive Virtual Environments (IVEs) are a particularly interesting case of such technology (Bailenson et al., 2008; Blascovich et al., 2002; Limniou et al., 2008; Loomis et al., 1999; Raja et al., 2004). A specific example of immersive technology recently highlighted is that of the digital fulldome (Lantz, 2006, 2007; Law, 2006; Wyatt, 2007; Yu, 2005). However, in comparison with other IVEs, little empirical work has been conducted to understand the impact of fulldome environments on audiences, despite their widespread and diverse uses.

The aim of this review is thus to start developing a framework within which to examine the properties of fulldome environments as particular examples of IVEs. We will review the state-of-the-art of existing IVEs, and what is known about the technology and its influence on cognitive factors. The work has implications for both psychological research and for defining optimal standards for application of the fulldome technology in, for example, formal and informal learning. We will first describe features of the fulldome environment and compare them to those of other existing immersive digital environments. We will then review core areas of psychology relevant to experiences in the fulldome, which include visual perception, attention, memory, social factors and individual differences. Within these reviewed domains, we will outline potential directions for empirical investigation.

1. The digital fulldome: A novel Immersive Virtual Environment

A digital fulldome describes a large immersive, dome-based video projection environment. Fulldome environments are typically derived from planetaria. Prior to the use of digital technology, planetaria featured mechanically

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operated projectors that cast points of light on the inside of a dome to represent the night sky, with the first dome planetarium opening in 1926 in Munich, Germany. In the entertainment industry, more recent developments in large-format cinema technology, such as the IMAX theatre, led to the design of wrap-around cylindrical displays such as the OMNIMAX cinema format, intended to fully immerse viewers in the presentation. As computer technology became more prominent, digital technology became incorporated into planetaria and the use of these environments diversified, to include non-astronomy-based entertainment and education applications (Lantz, 2007). The spherical surface of the digital fulldome can be used as a canvas for real-time or pre-rendered computer animations, live-capture images, or, in principle, any other visual projection accompanied by surround sound. Digital fulldome environments thus have applications in education and entertainment across a wide range of disciplines.

Fulldomes typically use single or multiple projection systems to display an image on the inside of a dome surface, with the intention of completely filling the viewer's Field of View (FOV). In contrast to other spatially immersive environments such as CAVEs (Cave Automatic Virtual Environments; Cruz-Neira et al., 1992) fulldome projection consists of a seamless wrap-around display. A particular benefit of the fulldome is the ability to accommodate large groups of viewers (typically 100+ individuals), thus making possible shared virtual reality experiences for a large audience, which is especially relevant for potential use in education (Lantz, 2006).

Following the definition of IVEs as environments that perceptually surround the user (e.g., Bailenson et al., 2008), the digital fulldome qualifies as an innovative medium through which to present content for a multitude of potential applications.

There are currently more than 700 digital dome theatres in operation in the world (Loch Ness Productions, 2012). They include large facilities open to the public, such as the Hayden Planetarium (American Museum of Natural History, New York), the Griffith Observatory (Los Angeles), Planetarium Hamburg, the Gates Planetarium (Denver Museum of Nature & Science), multi-use facilities such as the Norrkping Visualization Center, Sweden, and smaller experimental installations such as the Immersive Vision Theatre at the University of Plymouth, UK. The fact that many fulldomes are located within educational contexts emphasizes their potential for teaching and learning.

2. Immersion and presence

Although little research has been done in the fulldome, research from other immersive environments such as CAVEs and head-mounted displayes (HMDs) can inform an understanding of its effects. Two terms that frequently appear in the literature on such immersive environments are *immersion* and *presence* (e.g., Schubert et al., 2001; Slater, 2003). Although they are occasionally used interchangeably, the current review will follow the definition proposed by Slater and colleagues (e.g., Slater and Wilbur, 1997; Slater, 2003), which describes immersion as the objective, quantifiable features of the display that result from the particular software and hardware, and the extent to which they are comparable to the level of sensory input that would be received in the real world. In contrast, Slater (2003) defines presence as the subjective state of feeling as if one were in the environment and the degree to which the user responds to the display environment as if it were real (Sanchez-Vives and Slater, 2005). Slater (2009) further refines these two elements of presence, identifying the sense of being in the virtual place as place illusion (PI), and the degree to which users believe occurrences in the IVE are actually happening as the illusion of plausibility (Psi).

Although an assumed association between increased levels of presence and improved task performance is pervasive in the literature, reviews have cautioned that there is only limited and inconsistent evidence for this relationship (Nash et al., 2000; Schuemie et al., 2001). The suggestion that presence can be identified by 'realistic' task performance, in designs that compare real world performance to that in an IVE, further complicates this relationship because of the risk that performance and presence measures are circular. Slater et al. (2010) suggest a methodology based on simulating a new environment to a real one that was initially experienced, by manipulating factors (e.g., lighting, presence of an avatar) until they are equivalent. Similarly, Bowman and McMahan (2007) propose that immersion should be considered a multi-faceted concept of which components can influence performance directly. Using this approach, each sensory domain (e.g., visual, auditory, haptic) can be broken down into relevant factors (such as display size or stereophonic sound) that separately, and in combination, influence psychological processes. This approach allows establishing direct relationships between specific aspects of the immersive environment and performance, as opposed to it being an unspecified by-product of the subjective state of presence. A further benefit of using this multi-faceted approach to immersion is circumventing the problem of comparing environments based purely on self-report measures, given that their validity is unclear. For example, Usoh et al. (2000) examined two commonly used questionnaires to assess presence in both real and virtual environments. They found that the measures failed to distinguish between the two types of environments when participants completed identical tasks in both a real and simulated office, thus calling into question the validity of those measures to appropriately capture presence. Slater (2004) goes further to suggest that questionnaires are generally inadequate in establishing the concept of presence. Potential alternatives include physiological measures and automatic behavioural reflexes (for a review, see Insko, 2003); however, these measures are more challenging to use, especially in the context of having multiple users in the environment, as is the case with fulldomes.

General issues of presence and immersion (for reviews, see Ijesselsteijn and Riva, 2003; Slater and Wilbur, 1997) are as relevant for fulldomes as they are for other IVEs. Display environments such as the University of California's AlloSphere, as well as smaller scale technologies such as 'reality theatres' (curved horizontal displays) particularly bear similarities in the way in which they wrap around to immerse the viewer. Lantz (1998) speculates whether spherical displays create a more natural perspective for the viewer, an issue worth exploring (in contrast to flat screens and CAVEs) as these display types become common. Though immersion in the broad sense is a common goal in the field of IVEs, different technologies attempt this through different means. Developments with these technologies should be considered complimentary to fulldome research, and vice-versa, though it is critical to consider common and unique aspects of display environments in relation to performance benefits.

An additional critical issue for the fulldome is the fact that typically several viewers are in the same space, albeit with slightly different viewing perspectives. Thus, the co-presence of others in the same physical and virtual environment might modify each individual's experience. Bailenson et al. (2008) empirically tested the notion of "transformed social interaction" within learning contexts involving HMD-type virtual environments; similar issues may need to be investigated within the social context of a fulldome, as we will review in detail further below.

Overall, as is the case with other IVEs, the use of subjective measures as indicators of presence in fulldomes has to be reconsidered, and questionnaires may need to be supplemented with more objective measures such as behavioural assessments and psychophysiological monitoring, as well as assessments of the influence of other people's co-presence.

3. Psychological processes relevant to the digital fulldome

The aim of the main section of this article is to ground various aspects of immersion and presence in the fulldome in terms of fundamental cognitive processes and use these as a framework to predict potential benefits arising from the use of fulldomes.

3.1. Visual perception

The most prominent feature of the fulldome is its distinct visual display; thus, implications in terms of visual features and processing need to be examined. Bowman and McMahan (2007) summarize visual display elements relevant to immersive displays, of which we discuss frame rate, display resolution, display size, FOV, and Field of Regard (FOR) because they are particularly relevant to fulldome presentations.

Differences between display specifications have been highlighted within the fulldome community, with calls for a standardisation of criteria and an increased understanding in potential discontinuities (Lantz, 2004; Thompson, 2004). The variation in screen formats is a point of consideration for both content developers and those interested in application and research. As many digital displays are fitted into existing planetarium installations, and other constraints will vary, there is a concern that the viewer's experience of content is comparable across different domes. Content portraying scenes from a perspective centric to the viewer's gravity may appear disorientating if not modified from a horizontal to a tilted dome. This can be adapted more easily on rendered content, though may not make optimal use of the displays in some situations. The seating arrangement and screen format may also not offer an optimal perspective for all viewers in the dome, in contrast to single user systems in which the display can be tailored to a single perspective. For example, if a viewer is positioned close to the wall of the projection screen, their experience may be affected by spatial distortion on the periphery of the projection. This may not be an issue for all domes and content, though some situations may warrant a limitation of the number of viewers below the capacity of the theatre.

3.1.1. Frame rate

In other IVEs decreased frame rate has been shown to lead to decreased task performance (Richard et al., 1996), as well as a reduced reported sense of presence (Barfield and Hendrix, 1995), although increases over 15 Hz produce minimal gains in the latter. For many visual display factors it is important to establish critical levels of fidelity of the display environment; indeed, minimum standards for technical specifications of the fulldome have been outlined (Lantz, 2004). The typical frame rate for fulldome productions has been noted as 30 fps, with up to 60 fps possible on many systems (Lantz and Fraser, 2010).

3.1.2. Display resolution

Due to the requirement of projection onto a large surface area, display resolution can be a limitation with current fulldome technology compared with other media (Lantz, 2006). Empirical investigations need to examine whether this impedes performance significantly, or whether such a limitation could be overcome with other visual cues, and ultimately, the advancement of technology in the fulldome. Lantz (2007) provides a survey of dome video displays, noting projector resolutions ranging between 1024×768 and 5120×4096, with 4000×4000 being the current standard for many productions.

3.1.3. Display size

Because the average fulldome display is much larger than most projection based displays, past research examining display size is relevant. Larger screens provide an advantage over small screens on some spatial tasks, even when viewing angle is held constant (Tan et al., 2006). Tan et al. (2006) propose that a larger screen encourages the user to follow an egocentric spatial strategy for which the body is used as a frame of reference, in contrast to exocentric strategies based on the external environment as a reference. Using computer display based tasks, egocentric approaches have been shown to benefit certain mental rotation tasks (Carpenter and Proffitt, 2001; Wraga et al., 2000)) and cognitive map learning (Bakdash et al., 2006; Tan et al., 2006). Interestingly, Tan et al. (2006) found that a large display did not produce an advantage in spatial tasks in which an exocentric strategy is optimal, thus highlighting the importance of considering the appropriateness of the task when examining possible advantages for IVEs.

Tyndiuk et al. (2004) suggest that a large screen advantage may be mediated by the factors of task demands and users' visual attention, because participants with slower visual search ability benefited from a larger screen in manipulation and travel tasks, whereas no difference was shown for faster participants. Similarly, Allen (2000) proposes that the general utility of computer systems varies greatly based on users' spatial and perceptual abilities. Baxter and Preece (2000) further suggest a compensatory benefit for a dome environment in school children. They found that female students improved their knowledge about astronomy after a planetarium presentation, but no such benefit occurred for male students, presumably because the task involved spatial ability for which female students might have benefited from the additional training. Thus, rather than improving performance in all users, fulldomes and other IVEs may serve as compensatory aids in domains in which some users' abilities are comparatively weak.

3.1.4. Field of view (FOV)

The fulldome display typically fills the viewers' horizontal FOV, as well as a large proportion of their vertical FOV, with precise coverage depending on the installation and seating position. FOV has been associated with performance on spatial navigation, map formation and visualisation tasks (Alfano and Michel, 1990; Creem-Regehr et al., 2005; Toet et al., 2007). Alfano and Michel (1990) suggest that because a great deal of information about the environment is processed in the periphery of people's vision, limited FOVs often decrease performance and can induce symptoms of discomfort. HMDs tend to have restricted FOVs, and thus, may lead to deficits in performance, postural stability and presence in users (Toet et al., 2007), although Lin et al. (2002) note that the negative relationship between FOV and performance aspects may plateau at a certain level. Whereas deficits in distance estimations in real environments when FOV is restricted can be overcome by allowing users more time to adjust their view and scan the environment (Wu et al., 2004), an environment that efficiently minimizes these downsides may be desirable, particularly with large scale environments. Additionally, peripheral information is a significant factor in producing sensations of vection, the perception of self-motion when stationary (Brandt et al., 1973). Thus, for applications relying on peripheral visual information, the fulldome provides an excellent alternative to more visually restrictive HMD displays.

3.1.5. Field of regard (FOR)

FOR refers to the extent to which the display surrounds the viewer, and is independent of FOV. An HMD typically has a 360° FOR, because users will view the virtual world no matter in which direction they look, whereas CAVE environments typically possess a 270° FOR, because they lack a rear projection wall (Raja et al., 2004). The FOR of a fulldome screen can vary between installations, with some providing a full 360° FOR and others featuring a break in the screen at the rear. Because many installations involve slanted seating and projection areas viewers are unlikely to turn their heads to the point at which the screen breaks. Based on preliminary observations, Raja et al. (2004) suggest that a higher degree of physical immersion, specified as using four screens of a CAVE rather than one screen, produced an increase in performance on some visualization tasks.

Jacobson (2010) compared the presentation of an educational game in a digital dome to a desktop screen. The game involved a guided tour through a virtual Egyptian temple that required correct answers in order to advance. Middle school children were recorded giving their own guide through the temple, and videos were rated for conceptual and factual knowledge. The recorded guides were significantly higher on both factual inclusion and conceptual explanations for fulldome compared to desktop presentation. Jacobson (2010) suggests that this may be due to the reduction in cognitive load afforded by the physical immersion in the environment, allowing participants to examine the spatial environment more efficiently. Furthermore, and in line with the suggestion of IVEs offering a compensatory benefit, this dome advantage was enhanced in participants who scored lower on Raven's Progressive Matrices, a test of reasoning ability.

In addition to the impact of screen size on spatial strategy, Bowman et al. (2002) have noted differences between IVE types and user preferences for egocentric and exocentric strategies. Bowman et al. (2002) found that users were more likely to turn their bodies to navigate (''natural turns'') when using HMDs than in a CAVE, as opposed to manually rotating the environment around them using a joystick. They suggest that natural turns, although slower than using the joystick, were less disorienting than quickly rotating the environment. Notably, the CAVE's structure does not allow natural turns through 360° because the rear wall is absent; thus manual turns (or a combination) might be required. Future work with the fulldome, and other spatially immersive displays, needs to assess whether the increased FOR facilitates performance for users, and if so, for which tasks such an advantage emerges.

3.1.6. Unique features of the fulldome

Because the display wraps around the viewer, additional factors that have been studied in other IVEs (e.g., head-based rendering and stereoscopy) are not typically implemented in fulldome displays; however, they are worth considering for the dome in comparison to other systems. Because head-based rendering allows HMD users to turn the orientation of their heads, the display of the environment follows their movements directly. In contrast, because the surrounding environment is pre-rendered in the dome environment, it is not as necessary to alter the image in response to changes in the user's orientation. Further, stereoscopic presentation in HMDs is used as a cue to create the perception of depth to the viewer. Stereoscopic fulldome content does exist (e.g., the 'Imiloa Astronomy Center' of Hawaii), but is associated with some difficulties, which bring into question how much it improves the experience over high-quality standard presentations (Howe, 2009). In multi-user contexts where head tracking is unfeasible, and there are potentially multiple interesting sources of information, predicting user's view can be difficult for systems that rely on generating contrasting sets of images relative to a particular point. The use of glasses which limit peripheral vision also has to be weighed against the benefits of a fulldome's increased FOV. If user friendly methods can be developed, stereoscopic rendering may be an option in the future, though currently, limitations with particular tasks may need to be overcome with alternative depth cues.

On the positive side, a potential benefit of the dome environment is the ability to visualize spatial relationships more efficiently than on a normal screen (Baxter and Preece, 2000; Wyatt, 2007; Yu, 2005). Although their utility is especially apparent for environments and processes that align with the dome's physical structure (e.g., astronomical processes), benefits are likely to extend to other aspects of spatial visualization due to the ability to represent space in three dimensions. Data visualisation is an example of an area in which other IVEs have shown great promise (Arns et al., 1999; Raja et al., 2004), with approaches varying from examining abstract data points in order to identify trends in plots (Arns et al., 1999), to addressing more complex contexts such as searching for specified elements within a virtual environment (Bayyari and Tudoreanu, 2006).

Approaches to data visualisation with computer technology have highlighted the concept of Situation Awareness (SA), such that a higher degree of awareness of elements of the environment and their meaning in a spatial and temporal context leads to enhanced user performance (Endsley et al., 2003). Endsley (1995) notes that SA encompasses several cognitive processes, such as attention, working memory and long-term memory. Endsley et al. (2003) and Bayyari and Tudoreanu (2006) specify three aspects of SA that can be addressed: the perception of data, the comprehension of data, and the prediction of future trends. The perception of data pertains largely to the extent to which the user can identify data elements, emphasizing performance in terms of perceptual speed. Bayyari and Tudoreanu (2006) note that display size is likely to influence speed in search tasks, with smaller displays minimizing the area that needs to be attend to, resulting in faster performance. Swan et al. (2003) found that desktop screens elicited faster search times in a map searching task than a CAVE, and wall and workbench IVE systems. However, more research is required to elucidate the precise effect of very large format displays, such as the fulldome, on visual search speed. As noted previously, Tyndiuk et al. (2004) found that a larger screen was an advantage in other tasks for users with slower visual search speeds, so performance trade-offs may be more relevant for some tasks than others.

Data comprehension is intuitively the domain for which fulldome technology shows great potential because digital planetaria have been successfully used to represent astronomical data in a format that allows viewers to visualize relevant structures and processes. Preliminary data from Arns et al. (1999) and Raja et al. (2004) suggest user benefits in identifying data features and trends on the basis of interactivity and physical immersion, respectively. Both groups of authors highlight immersion as a way to facilitate the conceptualisation of complex data sets, particularly multivariate data, and data that are more productively represented in three dimensions. The use of IVEs for such purposes has been proposed in various fields, including geophysics (Lin and Loftin, 1998) and neuroscience (Zhang et al., 2001). However, the kinds of data structures that could be represented more clearly or efficiently in a dome environment need to be established empirically, and the extent to which the lack of certain features such as interactivity and stereoscopic depth may impact visualisation within fulldome environments. The third aspect of SA, predicting future trends, focuses on the user's ability to extrapolate information from given information, and adopt an appropriate strategy with which to apply it for a given purpose. IVEs can support this process by optimally providing the information used to form predictions, as well as providing a flexible environment for users' to visualize potential outcomes.

In addition to being able to visually represent complex aspects of the immediate physical world, one benefit of computer simulation is the ability to represent environments and processes that humans are not normally capable of observing. For example, IVEs have been used to aid the visualization of abstract concepts in chemistry and physics (Limniou et al., 2008). However, as noted previously regarding leaning of spatial concepts, not all concepts may be aided by this representation, and it is possible for spatial relationships to be distorted in some circumstances. For example, Barfield et al. (1995) examined the effect of decreasing the Geometric Field of View (GFOV), namely the viewing angle from the centre of the projection to the edge of the display. Manipulations in the GFOV, relative to a fixed display FOV, lead to perspective distortions by magnifying or minifying the spatial relationships in the projection. Barfield et al. (1995) reported an increase in errors for judgments of relative location when the GFOV was decreased (i.e., when the scene was magnified). Similarly, Interrante et al. (2008) examined the effect of manipulating the size of a virtual room during training sessions, and found that participants underestimated distances in subsequent estimates in the real environment. Thus, content developers need to be aware of possible perceptual distortions on a fulldome screen, particularly in the case of transferring acquired judgments to real locations, and make optimal use of additional cues to indicate distance and size.

3.2. Attention

Attention plays an important role in virtual environments, particularly because presence has often been framed in terms of the balance of attention devoted to the real versus the virtual environment (Draper et al., 1998; Witmer and Singer, 1998). Although attention can be split between the two to varying degrees, Witmer and Singer (1998) suggest that there may be a threshold at which presence is achieved, and at which the 'real' world does not interfere with successful performance. Rather than associating increased degrees of presence with incremental increases in performance, presence should be considered as a minimal requirement in task performance (Nash et al., 2000). With respect to fulldome content and technology design, the minimal requirements need to be considered for presence to be achieved and maintained while learners are exposed to given content (Slater, 2002). Objective measures of presence have utilized situational awareness or cue detection tasks for which user performance when responding to cues in the real world is compared to the virtual environment (Draper et al., 1998; Riley et al., 2004).

On a neurological level, presence has been linked to decreased activity in areas of cognitive control, particularly the dorsolateral prefrontal cortex (Baumgartner et al., 2006; Baumgartner et al., 2008). Cognitive control within prefrontal regions has been implicated in top-down processing, including maintaining goal relevant information and selective attention (Miller and Cohen, 2001; Yeung et al., 2006). Such studies highlight the difficulty of manipulating visual content across presence conditions, which in this case concerned a roller coaster ride displayed on a flat screen. The high presence condition featured loops and turns during the ride, whereas the low presence condition consisted only of horizontal turns. As Slater (2003) notes, presentation content and presence can often be confounded; for example, it is problematic to assume lower degrees of presence in unexciting scenes. Nevertheless, the findings of these studies suggest that presence is associated with a lower degree of cognitive control. Interestingly, Baumgartner et al. (2008) speculate that children's tendency to reporting high levels of presence may be the result of implicated prefrontal regions not yet having reached maturity.

The relationship between presence, attention and performance is unlikely to be straight forward. Examining the role of difficulty for a visual search task in a virtual environment, Riley et al. (2004) found that greater presence lead to poorer performance. Similarly, Ma and Kaber (2006), using a virtual basketball hoop shooting task, demonstrated that presence was negatively related to task difficulty, and there was no association with performance. Perhaps difficult tasks are likely to frustrate because of perceived inability to control the environment, thus leading users to disengage from the task. Thus, in order to avoid disrupting users' attention within IVE tasks, instructors and researchers must be wary of presenting users with overly difficult or overwhelming material. Further, one possible challenge in the dome environment is the large display size, which can require more effort than standard displays to view whole scenes. As a consequence, this may increase the likelihood that specific information in complex fast-paced presentations will go unseen. Whereas smaller and single-user displays may be better able to manipulate the information that is attended at a given time, Lantz and Thompson (2003) note that content designers may need to create ways of directing multiple viewers' attention to items of interest within the display. This may place less of an emphasis on interactive content (at least in large audience contexts) in fulldomes, and more on operator-led presentations. As experimental examinations of attention involving performance measures based on perceptual speed or accuracy (e.g., visual search) will further need to address the issue of screen size differences between traditional IVEs and fulldomes.

3.3. Memory

Within educational contexts the potential effects of fulldome environments on memory are of considerable interest. To some degree, it follows that learning may be enhanced on the basis of the visual and attentional processes discussed above. Indeed, overlapping significantly with attention is working memory, for which the most prominent model was proposed by Baddeley and Hitch (1974) and Baddeley (2000). This model assumes separate storage and maintenance processes for visual and auditory information and a central executive component that allocates attentional resources. Within education theories of working memory and attention are often framed in terms of cognitive load (e.g., Sweller, 1988), with sub-components of working memory possessing a limited capacity for processing and storing information. Thus, overloading a subsystem can compromise performance, whereas demands on attention and memory processes can be reduced by spreading the same information across different modalities (e.g., visual and auditory information).

It may thus be productive to examine whether the fulldome environment utilizes the benefits of multi-modal immersive presentation to a greater extent than other media. Moreno and Mayer (2002) found that although multi-modal presentation was effective in both media, a HMD environment did not enhance learning to a greater extent than a desktop display, despite HMD users reporting a greater degree of presence. In contrast, Limniou et al. (2008) report better conceptual learning in students using an immersive CAVE environment over desktop software in the context of chemical structures and processes. Because the fulldome environment is largely limited to visual and auditory presentation it is particularly important to test the potential benefit offered by such multi-modal presentation. For empirical investigations comparing the exclusion of different modalities across environments (e.g., visual vs. auditory information, or both combined), identical information needs to be presented in all display conditions, with an effort to minimize information redundancy arising from multiple modalities.

Tan et al. (2001) discuss the benefit of space and location as additional memory cues, comparing a standard desktop screen to an ''Infocockpit'' consisting of three adjacent monitors in front of a larger, curved display screen, which displays an ambient visual scene. Participants were tested on their ability to recall three lists of word pairs, with each list being presented on a different monitor in the Infocockpit condition. Results showed a significant advantage in the number of word pairs recalled for the Infocockpit condition. It is important to identify whether this advantage came from the spatial distinction, or the background projection acting as a contextual aid to memory, although the use of spatial location as a memory aid is a useful element to explore further in all IVEs.

Some researchers have noted the utility of IVEs in the study of spatial and episodic memory, particularly for neuropsychological assessment and therapy (Rizzo et al., 2002; Wiederhold and Wiederhold, 2008). Because traditional screening tests for impaired memory systems have been criticized for lack of ecological validity, assessment techniques have been developed for virtual contexts. Matheis et al. (2007) note the utility of IVEs in demonstrating how impairments in traumatic brain injury patients map onto specific deficits in everyday activities, reporting lower rates of recognition and recall in patients in a virtual office environment. Wiederhold and Wiederhold (2008) encourage using IVEs for treatment for conditions such as Post-Traumatic Stress Disorder, because patients can be treated in a controlled representation of the environment in which their trauma occurred.

IVEs may benefit learning in certain contexts by efficiently tapping into cognitive processes such as episodic memory, which has been proposed to be reconstructive (Conway and Pleydell-Pearce, 2000; Tulving, 1983). Furthermore, the ability to reconstruct features in a coherent spatial and temporal context is required to recall episodic and spatial information, and to anticipate future events (Burgess et al., 2001; Hassabis and Maguire, 2007). Thus, IVE research could examine whether technology such as fulldomes can create a richer, more coherent spatio-temporal contexts for learning content, which may lead to improved recall. Comparing recall from a real-world seminar to a presentation using a desktop screen, HMDs, and audio only presentation, Mania and Chalmers (2001) found that the VE did not offer an advantage over other formats; recall of content was actually significantly worse in the HMD condition compared to the real seminar. The decrease in performance in comparison to the real seminar may relate to the novelty and unfamiliarity of the technology, rather than the ability of the technology to represent the material. Participants were also tested on their ability to recall the spatial layout of the environment, and no effect was shown. However, when participants were asked to identify their memory awareness and distinguish whether they simply 'knew' something, or whether they 'remembered' the source of the information, 'remembered' responses did show an increased likelihood of being correct in the HMD condition than in a real environment.

Although the conclusions to be drawn from Mania and Chalmers' (2001) findings are limited, and performance generally did not improve, this might have been because recall of lecture content did not specifically relate to, or was not facilitated by, episodic memory. Whereas attention and memory regarding the spatial environment may have improved in the HMD condition, this did not affect the recall of semantic information within the lecture, suggesting that educators may benefit from seeking to integrate such information more coherently into the environment. Bowman et al. (1999), using a virtual zoo environment to teach students design principles, suggested that making use of the ability to embed relevant text and other contextual information is more effective than simply digitally reproducing the environment. Bowman et al. (1999) compared performance on a test of environment content and zoo design knowledge between students with experience in a multi-modal IVE to students who had only received classroom instruction, with results not reaching significance, although the authors note small sample sizes and the presence of outliers. Further, students using the IVE had additionally received the same classroom instruction as the control group, thus, they received the information twice. Although such research suggests that IVEs can be used as effective learning tools, it does not address whether IVEs are more effective than other media, an issue that requires more in depth examination.

A great deal of research has examined the potential benefits of IVEs with regards to navigation tasks and spatial learning, elements of which have already been noted in Section 3.1.3 on Display Size. For example, Bakdash et al. (2006) found that larger desktop screens elicited an advantage in learning spatial environments, in which users were more accurate in pointing to the location of a landmark. Similarly, Patrick et al. (2000) examined spatial knowledge of landmark positioning in a virtual theme park, comparing performance on a map placement task after participants toured an environment on either a small display, large display, or HMDs. Both large screens and HMDs produced greater accuracy than small screens. In addition to the benefit of a large screen, the use of spatial cues may facilitate the formation of coherent cognitive maps of 3D environments. Shelton and McNamara (2001) note participants are better able to recall spatial layouts when the objects are aligned with structural features of the environment (e.g., walls) than when they are misaligned. Thus, it may be useful to examine the use and structure of 3D space within the fulldome, particularly when transfer of spatial knowledge to a similar or identical environment is desirable.

Within this context one needs to consider what specific aspects of the virtual environment contribute to effective spatial learning. A critical distinction is between active and passive training, which refers to applications in which users control their direction and motion, or in which they merely observe a given route (Bakdash et al., 2008; Keehner et al., 2008; Wilson and Péruch, 2002). Although evidence is mixed, and effects depend on the manner in which knowledge is tested (Wilson and Péruch, 2002), multiple studies have suggested that active navigation provides an advantage in spatial tasks (Carassa et al., 2002; Hahm et al., 2007; Péruch et al., 1995; Sun et al., 2004). Similarly, for smaller scale spatial tasks, although some evidence has shown a benefit for interactivity in tasks such as object recognition (Harman et al., 1999), other tasks such as inferring the structure of 3D shapes (Keehner et al., 2008) and data visualisation (Marchak and Marchak, 1991) have shown no advantage over passive viewing. Notably, in some contexts of spatial knowledge (Wilson and Péruch, 2002), data visualisation (Marchak and Zulager, 1992) and tactile maze learning (Richardson et al., 1981), active navigation actually resulted in worse performance than passive navigation.

Thus, although the dome is largely limited to passive use, this may not constitute a problem. Indeed, Keehner et al. (2008) propose that active interaction itself is not critical for successfully acquiring spatial knowledge. Interacting with a display allows users to develop their own strategy to learn the content; however, particularly with novice users, this strategy may not be optimal. Keehner et al. (2008) note a great deal of variability among users and report that users who passively viewed an optimal movement of the display performed just as well as active users. Thus, interactivity may not be an intrinsic advantage, but rather a means to abstracting the most useful information. Alternatively, Wilson and Péruch (2002) suggest that attention is a primary factor in distinguishing between active and passive environments, noting inconsistent effects between studies using different methods, and a lack of a difference when participants are specifically asked to attend to task specific features. Furthermore, these authors suggest that passive systems could facilitate complex tasks when an interactive element might detract from important elements of the display. Bakdash et al. (2008), however, suggest that simple attention allocation does not address the active/passive distinction, noting instead that active environments require users to make decisions about their goals within the environment. As a consequence, this need to make navigational choices provides a richer source to draw upon for subsequent tasks. Thus, Bakdash et al. (2008) propose methods of augmenting content in which active control is not available, such as the addition of visual cues including landmarks (Oliver and Burnett, 2008) and updated reports of user orientation and position (Parush et al., 2007). Additionally, they suggest that spatially orientated auditory cues may serve to alleviate workload on visual working memory systems, for example, using the sound of a river from a given direction to indicate its location. Within fulldome environments, designers and researchers need to determine optimal ways of presenting within the medium, and assess whether performance differences emerge relative to interactive tasks.

Overall, the avenues in which to explore potential memory benefits through the use of a fulldome environment overlap, or may indeed arise from factors noted in other sections. Memory for visual and spatial information, both on a small and a large scale, has been prominent in IVE research generally, and is equally critical to many applications of fulldome environments.

3.4. *Social factors*

Fulldome environments are unique among IVEs given their potential to show a single display to a large group of viewers simultaneously (Lantz, 2007; Yu, 2005). Although social processes have been examined using IVEs, most work has focused explicitly on whether social processes can be elicited by virtual agents, or between real agents within virtual environments (Blascovich et al., 2002; Hoyt et al., 2003; Pertaub et al., 2002). Bailenson et al. (2008) note that the absence of a social context in virtual environments designed for individual users is a potentially negative aspect in educational applications, because many educational theorists highlight benefits from social presence, interaction and collaboration (e.g., Bielaczyc, 2006; Wenger, 1998; Wood et al., 1995). However, a great deal of research has demonstrated that virtual agents can elicit social influences, such as inhibition (Hoyt and Blascovich, 2001), anxiety (Pertaub et al., 2002), risk taking and social comparison (Swinth and Blascovich, 2001) and proxemic behaviour (Bailenson et al., 2003). When social interaction is desirable, virtual agents may actually pose an advantage over real agents, because the designer has more control over the frequency of beneficial and detrimental behaviors, with the potential to adjust behavior in regards to an individual learner's needs (Blascovich et al., 2002). However, given financial, computational and practical constraints, it is likely desirable to have access to a medium that can accommodate larger groups of users, such as the fulldome.

Social processes especially relevant within the fulldome include social facilitation and collaboration. Social facilitation refers to the observation that participants perform better on practised or simple tasks in the presence of others compared to when alone, but perform worse on novel or difficult tasks (Zajonc, 1965). It may be beneficial to study this effect in regards to tasks performed after training within a fulldome, or tasks performed with some degree of expertise (e.g., astronomical data exploration with skilled users) to determine the extent and applicability of this effect in the environment. Previous research has demonstrated a social facilitation effect on a computer based tracking task (Corston and Colman, 1996). Data visualization frameworks, such as that of SA described previously, could be readily examined in a social context within fulldomes.

Collaboration between multiple users working together towards common goals has often been emphasized as a factor for technology to encourage learning within education contexts (Crook, 1994; O'Donnell et al., 2006; Schofield, 1997). Notably, the term Collaborative Virtual Environments has been coined by several authors (Kirner et al., 2001; Redfern and Naughton, 2002) to describe immersive environments that accommodate multiple users, typically as a result of networking individual units. Given the ability of fulldomes to accommodate multiple users, there is a practical opportunity to explore the role of collaboration in IVEs, allowing users to communicate directly, rather than through computer mediation. Much of the research examining social interaction in IVEs comes out of necessity, as a basis for widely distributed organizations and research teams being unable to meet in person. To this end, research has examined the necessary factors to facilitate social interaction. Representing non-verbal cues such as eye gaze through the use of avatars is something that has been shown to facilitate turn taking and interaction in virtual discussions (Bailenson et al., 2005). Nevertheless, some studies have found that word and on-topic sentence production is reduced in virtual discussions compared to when participants are physically present (Friedman et al., 2009). The impact of this may vary with the demands of the collaboration, with more complex interactions suffering from a reduction in detail. In situations where shared physical space is not impractical, an IVE such as a fulldome may serve to avoid such problems.

Given that the accommodation of multiple users is often highlighted with the technology, it is important for research to examine how both direct and indirect processes involved in social interaction are relevant to learning and task performance. For example, effects such as social facilitation or inhibition are caused by the mere presence of others, whereas the consequences of directly interacting with another person (i.e., talking, listening, etc.) in the dome may have very different consequences.

3.5. Motivation, affect and individual differences

3.5.1. Motivation

Anecdotal reports of positive feedback from viewers (Wyatt, 2007; Yu, 2005) suggest a potential for fulldomes to increase motivation, a factor particularly beneficial for educational and commercial use. Intrinsic motivation, based on internalized desires as opposed to external reward or incentives, is regarded to be critical factor for learning (Deci and Ryan, 1985, 2000). Thus, an engaging and enjoyable learning environment may well increase students' motivation towards a subject. However, one concern is that any motivational benefit may merely be the result of using a novel teaching method, and that any such potential learning benefits may wear off over time. Dede et al. (1996), using software that allowed users to examine and manipulate electrostatic processes within a 3D environment, reported that students' enjoyment ratings and performance advantages using a virtual environment were consistent after prolonged use. In order to identify the role of fulldome technology, long-term use has to be assessed to determine if there is a point at which enjoyment and potentially enhanced learning decrease. On the other hand, the possible frustration of initial inexperience with the environment is an issue to be considered within IVEs (Arns et al., 1999), although one that is reduced with the lack of direct user interaction with the system, as will be discussed later.

3.5.2. Simulator sickness

Simulator or cyber sickness describes negative symptoms experienced by users in immersive and virtual environments, which shares many symptoms commonly experienced in motion sickness (e.g., nausea and disorientation), as well as symptoms associated with viewing displays (e.g., eye strain). These symptoms have been associated prominently with HMD displays, with up to 80% of users experiencing some negative symptoms, and 5% of users experiencing severe symptoms (Cobb et al., 1999). Although advances in technology have led to decreases in the prevalence of symptoms (Bailenson and Yee, 2006), even a low prevalence is a potentially serious concern in applications such as education. Other display formats, such as desktop screens and reality theatres, have shown reports of similar symptoms, albeit to a lesser extent than HMDs (Sharples et al., 2007). In a study comparing a variety of navy flight simulators, Kennedy et al. (1989) noted that dome displays led to a comparatively lower prevalence of symptoms than other media. No systematic study on large scale fulldomes has examined the incidence of these symptoms. If negative symptoms are less pronounced in fulldome environments compared to other IVEs, examinations of factors contributing to simulator sickness within fulldomes could indicate how such factors can be minimized by content developers.

3.5.3. Experience

Previous exposure to virtual experience can change cognitive abilities. For example, experience in playing action-video games can lead to improved selective attention (Green and Bavelier, 2003) and better ability to switch attention (Greenfield et al., 1994). Similarly, in surgical training applications, gaming experience has been associated with increased speed and efficiency in virtual procedures (Enochsson et al., 2004; Grantcharov et al., 2003). In addition, some authors note that observed sex differences on spatial tasks in IVE may in fact be due to males having more computer gaming experience (Astur et al., 1998). In addition to Wilson and Péruch's (2002) suggestion that control devices could act as a distraction, having a trained operator manipulating the fulldome display in response to user feedback could bypass issues of user inexperience that have been implicated with other technologies (e.g., HMDs).

3.5.4. Individual differences in visual and spatial ability

A great deal of research has examined individual differences of spatial ability on small scale tasks, such as spatial span and mental rotation, and large scale tasks, such as landmark, survey and route knowledge measures of environmental learning (Enochsson et al., 2004; Stanney et al., 1998; for a review, see Hegarty and Waller, 2005). Hegarty and Waller (2005) note mixed findings across studies in this area, with the majority of associations not reaching significance, and few reported correlations of higher than .3 between paper-and-pencil measures of spatial ability and environmental knowledge. Further, Hegarty et al. (2006) found that the relationship between performance on small and large scale spatial tasks was significantly mediated by the format in which information was learnt, specifically, that small scale spatial abilities correlated strongly with those on a large scale when the large scale task involved encoding through the use of computer or video displays. Hegarty et al. (2006) suggest that these mediums place a higher demand on visual processing, with information being obtained almost exclusively through a visual modality, rather than other sources such as vestibular cues in real world navigation. In addition to highlighting a role for supplementing visual information with other sensory cues, this raises the consideration of how reliance on visual–spatial input affects user's performance, particularly when IVEs are themselves used to aid the representation of space.

Given a strong emphasis on the potential for fulldomes within education (Law, 2006), it is important to further clarify individual differences before learner needs and outcomes, and the question of how fulldome technology can meet these specifications.

4. Experimental considerations

Bearing in mind the aims and requirements of most fulldome facilities, some confounding issues arise when comparing tailor-made fulldome content to other formats. Othman (1991) notes that planetariums are typically used for commercial purposes and content creators must be aware of the entertainment value and the requirement to generate revenue. Additionally, fulldome shows are often guided by a presenter, who both narrates and manipulates the content that is being displayed. Although this does not detract from the prospective benefits of fulldomes, and indeed, may be advantageous in itself, it needs to be considered when comparing different mediums. In order to assess whether fulldome environments provide a benefit, and if so, how best to use it, it is critical to isolate the various factors during testing. This isolation of factors depends on the nature of the medium which the fulldome is being compared to: Whereas for some applications it may be appropriate to compare a fulldome display to a desktop display or other IVEs, for other applications it may be desirable to use traditional lectures with two-dimensional visual aids. The justification for this choice should be based on the particular research question, with additional considerations likely being necessary in regards to potential confounds across vastly different mediums.

Fox et al. (2009) distinguish between three avenues of research involving IVEs in the social sciences, framed as an object, an application, or a method. The IVE as an object refers to facets of an individual's experiences within an IVE, including aspects previously mentioned such as subjective feelings of presence. The IVE as an application refers to examinations of its efficacy as tool in contexts such as learning or skill training. Finally, IVEs as a method refers to contexts in which the technology is used as a tool study some psychological process more broadly (e.g., fear or social interaction). For example, using an IVE to examine social interaction is a different goal than comparing social interaction in a real versus a virtual environment, and the design of a given study will depend on the framework underlying it.

Associated with the choice of research question and comparison is the domain in which one might expect performance benefits. Although some applications may compare amount of recall of presented content, or some other measure of efficiency on the same task (e.g., completion time), it is important to consider how benefits may be applied outside of the context in which they are learnt. Bossard et al. (2008) and Dede (2009) highlight the transfer of learning as an important benchmark for IVE systems. In other words, to be effective, educational tools IVEs should facilitate the generalization of learnt skills and knowledge to the real world. Bossard et al. (2008) note that transfer is often difficult to isolate, often consisting of encouraging a mode of thinking within students that can be applied elsewhere, and that research in the area is sensitive to potential effects being masked by tasks being overly difficult or easy, as well as the new context being too different from the original. For these reasons, it would be beneficial to return to the discussed elements of immersion and features of fulldomes that are relevant to specific learning outcomes.

One example of this is using IVEs as a preparatory aid for field environments that are not easily accessible and in which time is limited (McMorrow, 2005). Research on students' experiences in fieldwork has highlighted factors that impede effective learning and performance, such as the role of geographical, cognitive and psychological factors in producing a successful field trip, collectively referred to as creating a 'novelty space' (Orion, 1993; Orion and Hofstein, 1994). McMorrow (2005), using a web-based resource, suggest that virtual environments in combination with instruction could be used to reduce the impact of geographical and cognitive novelty, by providing a comparable context within which to introduce relevant training, as well as introducing students to the spatial environment. Furthermore, researchers have recently suggested that social factors may heavily interact with other novelty space factors, or represent an independent factor in itself, with fieldwork being heavily rooted in an interactive social context (Elkins and Elkins, 2007; Stokes and Boyle, 2009). Fulldome environments lend themselves to the integration of social features in these training contexts that other technologies do not typically accommodate.

Presentation content is critical when comparing the effectiveness of fulldomes with other mediums; ideally, identical (or at least comparable) content needs to be presented across different display formats. However, it may be difficult to display dome-made content on other display media. Similarly, keeping content identical across media may wipe out the very advantage of the dome environment. For example, many standard low-level visual stimuli consist of simple shapes or arrays, for which one would expect little advantage for aspects such as FOV or display size. Because the nature of the stimuli for experimental purpose is integral to the aims of the research, it may be desirable to develop a standardized set of presentation content that can be used to test specific aspects of content across different IVE display systems.

Although the majority of this paper has focused on the application of fulldome technology to education, there is great potential for fulldomes, and other IVEs, as research tools in many of the reviewed content areas of psychology, or more generally, within cognitive science. Supporting arguments for the use of IVE technology have emphasized a higher level of ecological validity with content used, while still maintaining a high degree of experimental control, for both environmental features and social interactions (Loomis et al., 1999). Notably, in areas such as spatial cognition, IVEs allow for complex and highly controlled presentation and have featured prominently in research within the field (Astur et al., 1998; Kelly et al., 2007; Maguire et al., 1998). As stated previously, the use of IVEs has also been noted in its use for assessing neuropsychological conditions (Matheis et al., 2007), with tasks being better able to assess how cognitive deficits manifest themselves in real world task performance than standard questionnaire methods of assessment. Because IVE technology often seeks to represent environments to a more comparable degree to equivalent real-world situations than can be provided with standard mediums, there is a great potential for IVEs to be utilized as a method of presentation in many areas. With appropriate comparisons between performance within fulldomes and equivalent real world cognition, it would be useful to explore applications for fulldome environments as a tool for research, particularly given the ability to test large numbers of participants in single sessions.

5. Suggestions for possible research priorities involving fulldomes

In this paper we have considered a wide variety of existing findings that have potential relevance to applications of the digital fulldome in learning, teaching and research. A critical question now is: Where does one go from here? How can earlier findings inform potential avenues for future research, and which directions should be prioritized? We believe a research agenda investigating the following questions would be most productive. First, the main priority should be to empirically demonstrate clear advantages of fulldome presentations compared to traditional presentation formats used in educational context, where conveying maximal information to a high number of people is of utmost importance. Do fulldomes lead to better problem solving or recall performance when compared to information presented on a regular screen in a lecture hall, or a desktop computer? As noted above, methodological considerations in this context are that presentation content, and other contextual factors, need to be kept as identical as possible, in order to rule out confounding factors. Second, it needs to be clarified for what specific tasks and domains fulldome environments are mostly likely to provide educational benefits. Based on the existing research involving other virtual and immersive technologies, it is possible that the greatest learning benefits would occur for tasks involving a strong spatial components, either due to the nature of the task itself (e.g., spatial learning or navigation), or because complex facts and data can be more easily visualized and represented in three-dimensional space. This might be especially relevant for tasks requiring an egocentric representation, that is, relative to the perceiver, but less so for tasks requiring an exocentric representation. Third, an intriguing possibility is that enhancing learning opportunities such as the ones provided in a multi-modal fulldome presentation might be particularly tailored to individuals who generally have greater difficulty in visualizing complex circumstances, and in establishing mental and spatial models. Thus, studies on learning performance in fulldome environments should assess individual differences relating to various cognitive functions, to test whether some people derive more benefits than others. For example, do people who score low on spatial ability benefit more greatly from such displays compared to people who score highly?

Much remains to be done, but fortunately, there might be some aspects of the fulldome environment that, in our opinion, do not warrant much further concern at present. In particular, for learning benefits, we do not consider it paramount to create the most realistic or captivating experience regarding immersion and presence. Although this might be critical for dome applications created for entertainment purposes for which the experience of enjoyment is central, research to date does not support the conclusion that greater levels of immersion and presence lead to better learning, comprehension, and recall of information. This also suggests that small-scale dome installations such as portables domes could offer learning benefits comparable to their larger counterparts. Further, we also consider comparing fulldome presentations to other immersive environments such as those created on HMDs as a lesser priority, because the latter differ from the fulldome in too many important aspects, and would in any case not generally lend themselves to being used with ease in educational contexts with many simultaneous learners.

6. Conclusion

The aim of this review has been to outline a theoretical framework in which to examine cognitive processes within a fulldome environment, and to highlight potential avenues and challenges for experimental research. If prospective learning benefits are identified with the use of fulldome environments, the areas covered in this paper may need to be addressed in order to work towards a comprehensive explanation of those benefits. Research within fulldome environments can benefit greatly from existing research findings in other IVEs, although in addition to examining whether advantages proposed in these alternative mediums are applicable within fulldomes, it is important to provide direct evidence for their additional, unique advantages. The representation of space has featured prominently in IVE research in the past, because the visual elements of the display environment are typically the most prominent difference in regards to the elements of immersion, and this is also a critical element to explore within fulldomes. Further, the opportunity to explore social influences in regards to many of these applications could be highly informative to IVE research in general, and for the use of fulldomes in educational contexts in particular.

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