CONSTRUCTION HEALTH AND SAFETY TRAINING: THE UTILISATION OF 4D ENABLED SERIOUS GAMES

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SUMMARY: *Health and safety (H&S) is a major concern in the construction industry. Recent and historical data from the construction industry worldwide demonstrate that the human, social, and economic burden, inflicted as a result of H&S-related fatalities, is still significant. Training is a key strategy to reduce H&S risks. The investigation of serious games for H&S training in construction as complementary to traditional training methods has attracted significant interest in recent years. Current studies in this area have mainly focussed on scenario-led training where trainees interact with the same environment through pre-defined options in discrete game sections. This approach has limitations in terms of variety and amount of skills that trainees can learn. In this paper, the proposed approach is to enable a sandbox style serious game through the encapsulation of 4D (3D + time) concept in the game design with the hypothesis that this approach would influence the capability of trainee to spot safety hazards and the way they interact with the game. Such a serious game was developed for a real-world project which was modelled at three different as a replica of the planned schedule. The testing of the environment with 12 students demonstrated that combining serious games and 4D approaches can improve users' engagement and affect their abilities to spot H&S hazards.*

KEYWORDS: *4D modelling, H&S training, OpenSim, Serious games*

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1   INTRODUCTION

Health and Safety (H&S) in construction processes is a cross-disciplinary area concerned with protecting the welfare of all stakeholders of construction processes including workers, employees, visitors and pedestrians and create a safe working environment. The construction industry is one of the most dangerous industries to work in as measured by onsite injury rates and compensation payments (Culver et. al., 1993). Due to the high risk of this activity there have been a number of studies and research conducted on reducing risks inherited within the industry (McDonald et. al., 2009). A large number of construction accidents are caused by human factors associated with employees' actions, behavioural traits and competency (Addison et al., 2013). Health and safety training and awareness are some of the main areas that need to be considered to improve the state of the construction industry (Paton, 2009). The 'One Death is Too Many' UK government report was commissioned by the Department of Work and Pensions and has concluded that this represents a serious problem within the industry (Donaghy, 2009). The rates of both self-reported illness (Fig. 1) and fatalities (Fig. 2) in the construction sector by the UK Health and Safety Executive agency are consistently higher than in other industries (HSE, 2012).
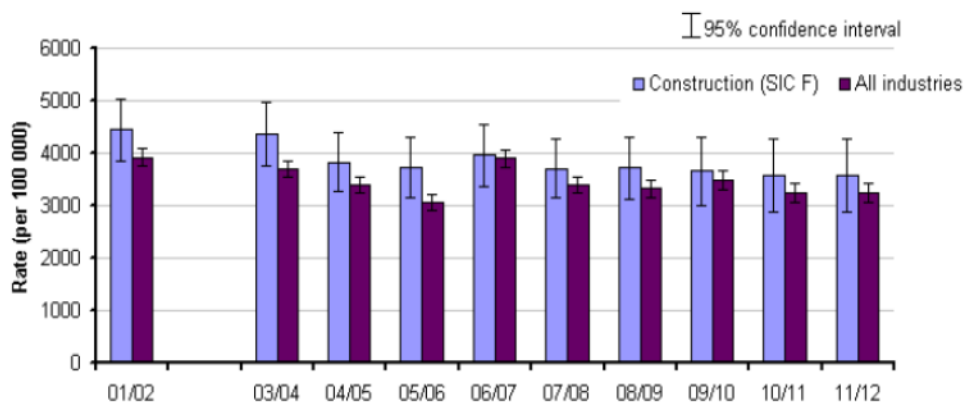

FIG. 1: Estimated prevalence rates of self-reported illness caused or made worse by the current or most recent job, per 100 000 people working in the last 12 months (HSE, 2012)
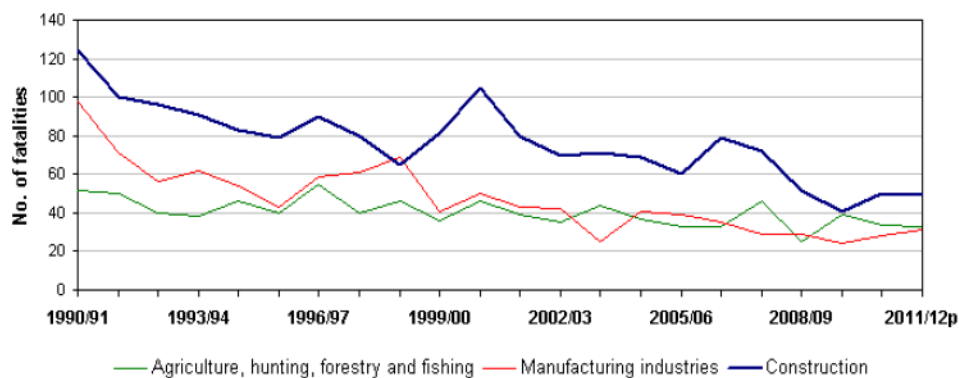

FIG. 1: Twenty-year trend in worker fatalities – 1990 to 2012 (HSE, 2012)

The HSE have also conducted case studies into common accidents that occur onsite (HSE, 2006). The data from the HSE report (2012) implies that one of the key areas for developing more effective training is in improving site awareness and imparting knowledge of spatial dangers that workers on site are exposed to. One of the main contributing factors to this injury rate is the lack of training given to workers and foremen on how to conduct these training exercises (Harrington et al., 2009). Research into serious games for H&S training in construction has attracted significant attention, since it can provide a cost effective and safe alternative to on-site training. Serious games or serious gaming refers to the use of computer games technology to generate tools to solve real

world problems. Research efforts to date, which are reviewed later, have been limited to discrete training environments where trainees interact with a pre-designed set of scenarios. In the subsequent sections, the research aim, objectives and hypothesis, the review of previous studies, the proposed serious game environment, its testing and results are respectively presented.

2 RESEARCH AIM, OBJECTIVES AND HYPOTHESIS

This research intends to explore the design of training tools in order to model the dynamics of a construction site evolving over time, and to support the construction industry in building and implementing a training environment suitable to its needs. For this purpose, an effort to provide a 'sandbox' style game environment is made through the merging of serious games and 4D planning approaches. 4D (3D+time) planning is a visual rehearsal of the construction activities that is enabled once 3D objects from the 3D model are linked to construction activities from the project schedule. Research into 4D CAD/planning tool started in the 1990s (Retik et. al., 1990; Williams, 1996) in an attempt to overcome the limitations of conventional construction scheduling techniques such as Gantt charts and networks in representing spatial requirements. In this research, the concept of 4D planning is embedded in the design of the serious game through the production of a virtual replica of a real construction site based on industry case study data (design and process data). The research hypothesis that drives this study is that a dynamic time changing virtual environment based on the combination of the sandbox approach with 4D modelling can influence the effectiveness of H&S site such as the capability of trainees to sport safety hazard. As a result, we aim to explore the use of the sandbox approach in the design of virtual training environments and understand how the combination of serious games and 4D modelling can improve user immersion and awareness of health and safety, particularly training in hazard spotting. To achieve this aim and test our hypothesis, we designed the subsequent objectives:

- To explore theoretical aspects of the research work including gaps in knowledge and research context.
- To develop a method and design specification for implementing a 4D construction site within a virtual world and to produce a virtual replica of a construction site based on industry case study data.
- To develop a pedagogy for implementing H&S training as emergent learning behaviour as part of the virtual training environment.
- To generate experimental data to provide understandings about the sandbox style enabled serious games.

3 LITERATURE REVIEW

Research analysing ways for improving health and safety in construction industry and emphasizing the need of new training approaches (Addison et al., 2013; Goldenhar et al., 2003; Kamardeen, 2013; Zhou et al., 2012) has proliferated in recent years. Construction projects require the contemplation of H&S issues since the early stages of project development and throughout the project lifecycle (Zhou et al., 2012; Kamardeen, 2013). Designers' decisions have a significant influence on H&S issues that can occur in later stages such as construction stage. However, the amount of risks left at the work interface within construction remains very high as evidenced by the H&S statistics presented earlier. In this context, recent developments in gaming technology have fostered new avenues and possibilities to improve H&S in construction. A number of drivers are influencing this phenomenon. Serious games have the ability to simulate innumerable conditions, while avoiding potentially hazardous and expensive field training. The application of serious games in construction can complement the work developed in earlier applications for the visual communication of construction activities (Dawood et al., 2006; Kam et al., 2003; Jongeling et al., 2008; Kang et al., 2007; Chavada et al., 2012), through the support of physics modelling (i.e. gravity, collision) and artificial intelligence that can be used to model worker interactions with the virtual environment. Serious games also offer the possibility of simulating issues that are not possible with field-based training, such as high risk activities (Lin et al., 2011). Previous research in this field has shown that the use of serious games is adequate for hands-on training purposes, which are most appropriate for construction workers (Addison et al., 2013; Dickinson et al., 2011; Lin et al., 2011). This includes the consideration of the outcome of workers' actions, which can contribute to reduce human-error based accidents in construction sites. Various studies have been focused on the use of serious games for hazard identification purposes (Chen et al., 2013; Chi et al., 2013). Hazard identification was also the focus of H&S training programs

aimed at the operation level using entity-based 4D CAD technology such as the Construction Hazard Assessment with Spatial and Temporal Exposure (CHASTE) tool proposed by Sacks et al. (2009). A review of recent developments in the use of serious games and related technologies for H&S training in construction is summarized in Table 1.

TABLE 1: Review of uses of VR, serious games and related technologies for the purpose of H&S training and simulations during the pre-construction stage

Approach	Focus	technology	source
Image-based location for an indoor VR-AR Immersive Environment Construction training system	Scenario led	mixed AR/VR	Carozza et al. (2013)
Safety training environment for construction hazard recognition and severity identification - based on training scenarios	Scenario led	mixed AR/VR	Chen et al. (2013)
Development of a trench safety game based on Construction Safety of Ontario training document	Scenario led	Game engine - Microsoft XNA Studio	Dickinson et al. (2011)
Development of a VR solution prototype for training of AEC professionals based on OSP (offsite production) practices	Scenario led	VR training environment	Goulding et al. (2012)
Proposal of a visual safety assessment system for hazard identification	Scenario led	Game engine - Unity 3D	Li et al. (2012)
A pilot study of a 3d game environment for construction safety education	Scenario led	Game engine - Torque 3D	Lin et al. (2011)
Development of a virtual training system based on a game engine for construction excavation operations	Scenario led	Game engine - Unity 3D	Wang et al. (2005)
Development of a game for Fire-safety evacuations based on BIM data using Triadic game design methodology (developed by Hartveld)	Scenario led	Game engine - Ogre 3D with Nvidia PhysX module	Rüppel and Schatz (2011)
Proposal of a methodology for the development of electrical safety training programmes in a VE considering Occupational Safety & Health Act (OSHA) regulations and industrial practice.	Scenario led	Game engine - Torque 3D	Zhao et al. (2009)
Scenario-based VR methodology (SIMCON+) to investigate logistic-related safety issues in construction sites, namely identification of conflicts that may occur on construction sites between temporary facilities, equipment, workers, and materials.	Scenario led	Game engine - EON studio	Naji et al. (2006)
Development of the ManuBuild Construction Site Training Simulator to be used for the training of project managers on new practice-based skills associated with off-site production.	Scenario led	Client-server: relational database + Cortona VRML client	Petridis et al. (2009)
Development of a serious game for the simulation of fire evacuation drills in modern buildings	Scenario led	Game engine - Source engine	Smith & Trenholme (2009)

Table 1 shows that applications of serious games and related technologies have covered various aspects of H&S that goes from hazard identification through risk assessment to risk mitigation and response planning. It also shows that with the exception of serious games for human rescue efforts (Smith & Trenholme, 2009; Rüppel and Schatz, 2011), current research has mainly focused on providing scenario-led virtual solutions (i.e. linear gameplay). Indeed, despite the availability of a variety of 3D-based game engines that allow the development of sandbox-based games, current efforts are still rooted in scenario-based design (Lin et al., 2011). Sandbox learning environments, based on non-linear gameplay are interactive virtual environments where users can engage in activities that are part of the core learning experience and in side-activities that have no direct connection with the core learning experience and serve to enhance the verisimilitude of the virtual environment from the user's perspective. The amalgamation of sandbox game style and 4D modelling approach to provide a serious game in which the effect of time on the capability of trainees to spot safety hazard is still unexplored area this research aims to investigate.

4 DEVELOPMENT OF THE VIRTUAL ENVIRONMENT

To test the research hypothesis, and following the sandbox approach, a full-scale site within the virtual environment was developed as a replica that ensures a truly open world environment. A complete site plan, project schedules and a temporary evacuation diagram including temporary structures in the site layout were provided by a construction company, Morgan Ashurst, who agreed to be part of a case study, and were used in the development of the virtual environment. To create this virtual site, the 'OpenSim' platform was used. OpenSim is an open source multi-platform, multi-user 3D application server. This platform was selected because of inbuilt functionality that supports multiple users interacting with both the environment and each other. The building schedules and 3D models were manually imported and encapsulated into the environment. Some considerations were taken in order to provide a sandbox experience. Instead of developing predefined linear training scenarios, pre-set instances for hazards were modelled throughout the virtual site at different weeks, reflecting the actual planned construction schedule, and the trainees can navigate anywhere in and around the virtual construction site. This way, the users can visually identify and report the hazards, providing them with a more realistic experience of what goes on in a real construction site from a worker's perspective. The identification of hazards by users of the virtual environment also aims to increase the engagement of users through increased awareness, providing transferable skills for the work on-site. Using a 4D modelling approach, the model was built up in a series of sections that reflected construction processes as would be the case in a 4D modelling tool. These sections were then grouped by task, using their textures and spatial position to visually identify which structures belong in which tasks. The development of the environment in this fashion allowed the virtual site to be linked with the project schedule to emulate an evolving construction environment. The navigation between sections in the virtual environment was achieved through the use of 'Holodeck' technology. This is a process whereby the environment within OpenSim can be changed from one world to another through the use of a simple command. This replicates the effect of the time axis that would be present in a traditional 4D model. By linking the individual models to the start and finish dates of each task this technology can be used to display how the site appears at any point on the timescale the simulation or scenario requires. The 4D modelling approach is intended to complement the sandbox approach by providing users with added sense of realism through the inclusion of different hazards that occur at different points in time in the changing environment of the construction site.

5 TESTING OF THE VIRTUAL ENVIRONMENT

In order to validate the research hypothesis defined at the beginning of this research, tests were developed to evaluate trainees' abilities to spot H&S hazards in the virtual environment and to understand how their performance varies in different points in time during construction. Trainees were separated in groups according to their previous experience in games and H&S training and their feedback was recorded in order to improve the system in the future, considering the influence of trainees' background.

To test the effect of this game design approach on the ability of trainees to spot H&S hazards, a number of hazards were modelled throughout the construction site at different stages of building development. An activity worksheet was developed so that the participants can record what types of hazards they found while exploring the environment on the different weeks. It also included a brief overview of what the session was about and details on logging in to the environment. As an example, a list of modelled hazards for week 1 is displayed in Table 2.

TABLE 2: List of on-site hazards for week 1

	Week 1 Hazards	Hazard Type
h11	Loose cabling around first floor	Loose/Untidy cables
h12	No railings on stairway	Improper stair railings
h13	Rubbish blocking stairway	Pathway obstructions
h14	Gas tanks unsafely stored	Poor storage
h15	No Railings around pool	Missing railings

Circa 70 hazards were modelled in two stages of testing. Tests were performed on 5 groups of subjects encompassing research students, undergraduate students, and college students in engineering and construction fields. This paper reports the results from tests conducted with 12 students from college, specialising in building construction. The tests were carried out in the Teesside University CAD labs using Singularity Viewer to access the test environment. The testing involved the identification of hazards by the test subjects and in answering a score-based 10 question feedback sheet.

The results from the hazard identification analysis are presented in Fig. 3 and 4. Fig. 3 shows the performance of each trainee in terms of amount of hazards identified in different weeks. In Fig. 3, each data point is scored out of a maximum of five, corresponding to the number of hazards present in the environment in any one week. This data shows that in the majority of cases, trainees recognised more hazards in week one than in the following weeks. Fig. 4 illustrates trainees' performance in terms of type of hazards spotted in different weeks. Each data point is scored out of a maximum of three, corresponding to the number of weeks where the hazard could be spotted in. This seems to show hazards hx1, hx2 and hx4 being the most consistently recognised and recorded by trainees. Hazards one and two were expected to be easily noticed, as they are the most visually distinct of the five hazards. With hazard four it is likely that this particular group of trainees explored areas of the site where that hazard was more predominant and were less thorough in areas where hazards three and five stood out.
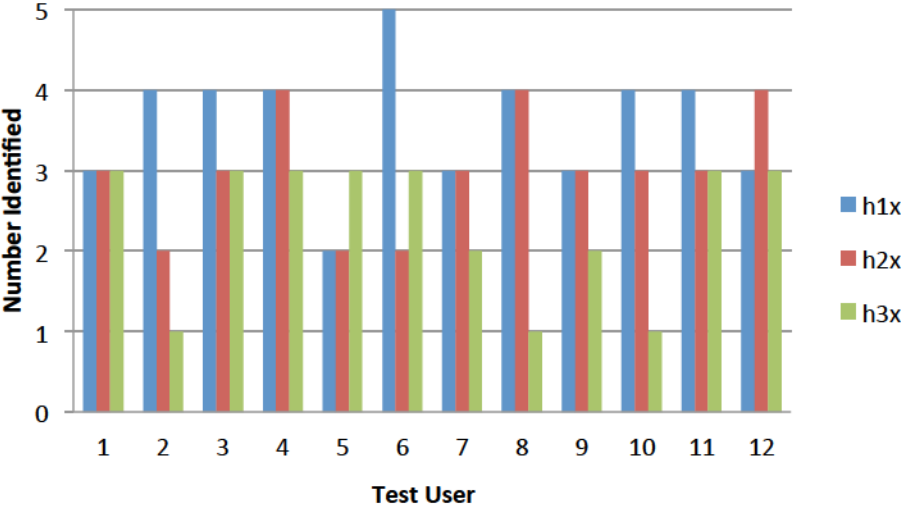

FIG. 3: Number of H&S hazards identified by each trainee week by week
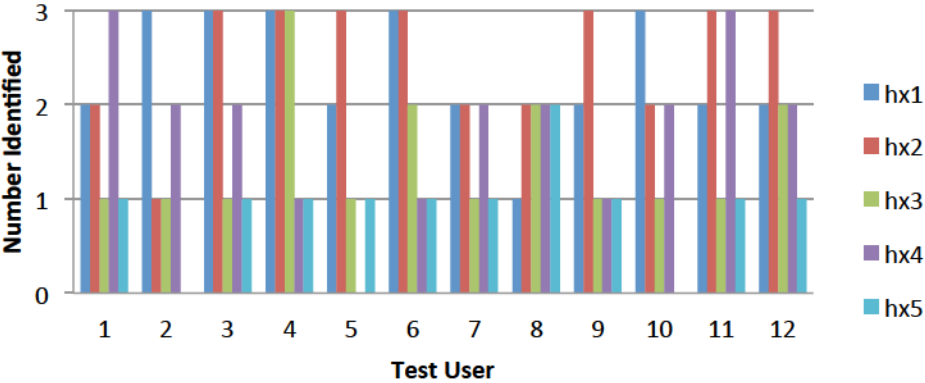

FIG. 4: Type of hazards identified by each trainee on each week

In order to assess users' experience of the virtual environment, a questionnaire was created. Criteria considered for the questionnaire were based upon that used by Makane and Dawood (2009) for a prior evaluation of computer based engineering tools. A set of ten questions was selected to provide a range of useful feedback on how the users reacted to the technology. The general aim of these questions was to evaluate the effectiveness and general feeling of the end users regarding the prototype environment. Each of these was rated between one and six, with one being a poor performance or bad experience and six being a good performance or good experience. Users' answers to the questionnaire were gathered in 5 groups considering users' previous knowledge of Health and Safety and previous gaming experience. Table 3 lists the questions used to elaborate the questionnaire. Fig. 5 establishes the overall comparison of different groups' answers to the questionnaire.

TABLE 3: List of questions to obtain feedback from users

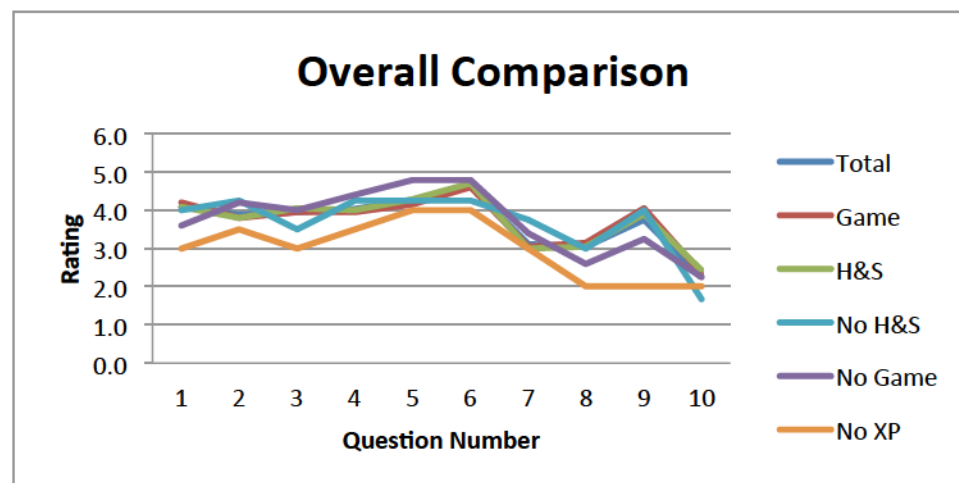|	Questions
1	Did you enjoy the game?
2	Were the graphics and components easily identifiable for their functions?
3	Were the gameplay mechanics intuitive?
4	How satisfied were you with the interface?
5	How satisfied were you with the ease-of-use of the program?
6	Was it easy to navigate in the game world?
7	Were there enough activities in the game?
8	Do you feel as though you have learned anything from playing this game?
9	Fun (i.e. positive aspects)
10	Annoyance (i.e. negative aspects)

FIG. 5: Overall comparison of different groups' answers for the questionnaire: Game – group of users with previous game experience; H&S – group of users with previous health and safety training experience; No H&S - group of users without previous health and safety training experience; No Game – group of users without previous game experience; No XP – group of users without previous experience in either games or health and safety training

The data in Fig. 5 shows that users with previous gaming or H&S experience track closely to the total average. Those without either gaming or H&S experience have larger divergences from the total. That could be an indication that aspects of the testing were problematic for them because of this lack of experience. Of note, the fluctuations of the response above and below the average total are not on the same questions. This highlights the areas that people lacking experience in certain areas find problematic in the virtual environment. The stand out group, however, is that of users with neither gaming nor H&S experience. This group scored below any other group on most questions with the only exceptions being questions number seven and number ten and was the only group to have an overall negative experience of the environment.

6   DISCUSSION

During the development of the virtual environment several issues were observed regarding asset creation and interoperability. Various features of the construction site were limited in appearance by the size and quality of texture files that could be created and imported into the development environment in use. This resulted in a decrease in visual quality for the environment, which according to users' feedback had an impact on their performance.

The use of 4D elements in the virtual environment proved to have an influence on users' ability to spot hazards. As the site progressed, users had increasing difficulties in spotting hazards on-site as evidences by the experiment with the decreasing number of hazard spotted on week 2 and 3 compared to week 1. This can be attributed to the increasing complexity of the site and is a reflection of the real world situation where safety incidents occur in more complex sites. This suggests that the combination of 4D modelling with a sandbox style environment should be further exploited despite current interoperability issues that are resulting in time consuming and expensive development. In accordance with the notion that a sandbox environment can provide side-activities that have no direct connection to the core learning experience, the testing showed that the majority of the testers included hazards that are not part of the testing schema but that would be an issue on a live construction site such as the lack of a welfare office or a manned first aid station. Others were un-documentable hazards based on user behaviour of other trainee sharing the same environment, like running on site or people not wearing the correct PPE. Such events fit the definition of unintentional emergent gameplay, which is often enabled by sandbox environments, where users take advantage of the large array of the virtual environment's capabilities for purposes unforeseen by the VE developer. These feedbacks obtained through the immersion of trainees in a sandbox game environment should be considered, subject to scrutiny, in future design refinement of the training environment.

Feedback obtained from the questionnaire demonstrates that while general user satisfaction is above average, students without game experience and/or health and safety training experience performed worse than students with experience in either field. Future developments should take these results into account in order to improve the engagement of users, especially those without previous experience in either games or H&S, in order to enable the transfer of knowledge irrespective of the users' previous knowledge in these fields.

Despite the limitations of the relatively small sample (12 students), these findings suggest that sandbox style games combined with 4D modelling has an influence on the capability of training to spot safety hazards and could provide the basis for iterative design of better virtual environment for safety training.

7   CONCLUSIONS

The main aim of this research work was to develop a virtual environment to support H&S hazard spotting in construction sites. The reviewed research in the areas of serious games for safety training revealed that the majority of environment are scenario led and does not consider the effect of site progress (time) on the training outcomes. This research by combining sandbox style with 4D (3D+time) planning approach aimed to provide a serious game where the effect of non-linear gaming and time on the training outcome can be analysed. Using this approach, a full virtual replica of a construction site that emulates the progression of construction over time was produced based on real world data. The resulting environment was a multi-user training environment created using the OpenSim platform. The testing of the environment showed that a combination of 4D and gaming approaches in a sandbox style environment can influence users' engagement and affect their abilities to spot safety hazards. The virtual environment showed that as the site becomes more and more complex over time, the ability of testers to spot hazards decreases. This suggests that such an approach can be useful if it is exploited in developing virtual environments to train workers on hazard spotting at stages where the site is complex. Moreover, the use of the sandbox approach provided side activities, not originally part of the testing methodology, to include additional training elements. This approach contributes to the state-of-the-art as the effects of sandbox style and 4D planning on the experience of trainee in virtual environments were not designed and measured in previous studies. The current limitations in implementing the proposed approach are related to the lack of interoperability between game and 3D environments. Future developments should focus on lessons learnt from this research, including the influence of the virtual environment design on users without previous knowledge of VR and/or H&S training methods, the use of the H&S feedback from trainees' side activities in the iterative design of the virtual environment and finally the exploitation of the combined approach of sandbox and 4D modelling in serious games development in highly complex construction site.

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