VIRTUAL AND AUGMENTED REALITY FOR HUMAN BEHAVIOUR IN DISASTERS: A REVIEW

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ABSTRACT

Natural and human-made disasters, such as earthquakes, fires, terrorism attacks, constantly threaten humans and their built environments resulting in loss of human lives and damage of properties. To reduce the impact of these disasters , it is fundamental to design buildings to allow people to respond safely and to train people on the best response to have depending on the nature of the disasters. Today several new technologies have been proposed to achieve these goals. Augmented and Virtual Reality represent some of the most popular technologies that have been adopted to achieve these goals. This work provides a review of existing applications and identifies common trends and research gaps. This review has identified 64 papers using Augmented and Virtual Realities to enhance safety design of built environments, to investigate human behaviour and to train people.

Keywords: Human Behaviour; Disasters, Augmented Reality; Virtual Reality; Evacuation.

1. INTRODUCTION

Every year several disasters affect humans and their built environments resulting, in some instances, in high numbers of injuries and deaths. These dramatic events highlight the need for enhance the safety of humans and reduce their risk of being injured or killed by a disaster. Two risk-reduction approaches can be used to achieve this goal: improving the design of built environments and improving the training of the populations at risk (Bernardini, D'Orazio, & Quagliarini, 2016; R. Lovreglio, González, Feng, Amor, & Spearpoint, 2018). The first goal can be achieved by designing build environments which allow people to respond to an emergency following appropriate procedures and strategies, for instance, *evacuate* immediately in case of building fires, *drop cover and hold* during an earthquake, *run, hide and fight in case* of shooting events (Bernardini, Lovreglio, & Quagliarini, 2019; Gwynne et al., 2017; US Department of Homeland Security, 2020). On the other hand, people need to be aware of which response is the most appropriate, depending on the type of threat. As such, safety training is paramount, especially for populations at risk.

In the last decades, many new technologies have been proposed to support the reduction of the impact of disasters on human and built environments. Among them, Virtual Reality (VR) and Augmented Reality (AR) represents two emerging technologies which have proven, in several instances, to support the design of safer built environments and enhance the safety training (Kinateder, Ronchi, Nilsson, et al., 2014; Ruggiero Lovreglio & Kinateder, 2020). These technologies rely on different combinations of hardware and software and are becoming popular as they are now available to the public. As such, it is fundamental to learn from the existing literature to understand the potentials and limitations of these two emerging technologies.

This work firstly aims at providing definitions of VRand AR and explain their possible types of hardware setups. The second goal of this paper is to provide an overview of existing applications of VR and AR to enhance the safety design of built environments and support disaster safety training.

2. VIRTUAL & AUGMENTED REALITY

In the last decade, AR and VR have become very popular in multiple research fileds as well as among the public (LaValle, 2017). This has been possible thanks to the release of mobile pieces of hardware and software which are now affordable and mature enough to develop customised applications. Both VR and AR aim at providing users with virtual (i.e. digital) contents. Still, they differ from each other in terms of how virtual content is intertwined with the real world (Ruggiero Lovreglio & Kinateder, 2020).

To highlight the differences between VR and AR, Figure 1 refer to the conceptual framework proposed by Milgram & Kishino (1994) who proposed a virtuality continuum between real and virtual environments. As such VR represents the extreme of this continuum and can be defined as a completely synthetic experience where users are presented with only virtual contents. The framework also identifies several mixed reality technologies which combine real and virtual content. As such, AR can be defined as mixed experience in which the main component is reality while the digital components (i.e. holograms) are a secondary components. The framework finally introduces Augmented Virtuality (AV) in which the balance between digital and real components is opposite to AR. In AV, physical elements, such as physical objects or people, are dynamically integrated into the digital environment. However, AV is out of the scope of this paper and is not discussed any further.

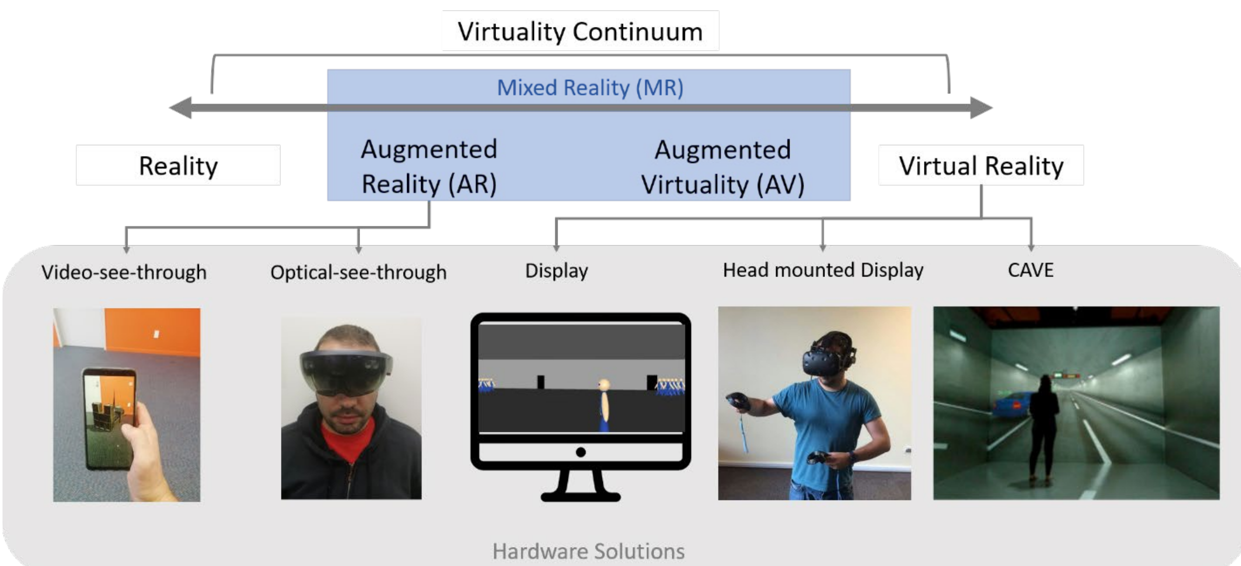

Figure 1: Virtuality continuum by Milgram & Kishino (1994) and hardware solutions for VR and AR. This figure uses modified figures published in (Ruggiero Lovreglio, Borri, Dell'Olio, & Ibeas, 2014; Ruggiero Lovreglio & Kinateder, 2020; E. Ronchi et al., 2016).

AR and VR can be classified on the base of the hardware solutions. VR technologies can be categorised into immersive and non-immersive solutions. Non-immersive VR can be achieved by visualising the virtual content by using a display. As such, traditional videogames represent instances of non-immersive VR. Immersive VR experiences can be obtained by using technologies such as Head-Mounted Displays (HMDs) or Cave Automatic Virtual Environments (CAVEs).

HMDs provides users with a couple of displays (this solution is preferred for dedicated VR headsets) or a single display which is divided into two sections (this solution is used to adapt smartphones for VR experiences) one for each eye. As such, each eye is provided with two videos slightly shifted, which gives the users the "illusion" of a tridimentional view. One of the main challenges for HMD is the users' movement with their view of the digital environment. The tracking has been achieved using three different solutions. The first solution is the use of tracking stations, as illustrated in Figure 2.a, which allow the tracking of users' movement is a defined tracking area using two or more infrared tracking stations. The second solution is based on the use of Visual Simultaneous sLocalisation and Mapping (SLAM). In this case, HMD has multiple cameras whose videos are used to locate the headset in the space using references points in the real space and triangulations (see Figure 2.b). The last solution is based on gyroscopes. In this case, the device uses gyroscopes to track the rotations if the headset along three axes, as shown in Figure 2.c. The first two solutions allow detecting both rotations and translations of the headset while the third solution detects only rotations. As such, users cannot translate in digital space by simply translating in the real space. This solution, although not optimal, is generally used for VR experiences run through smartphones.

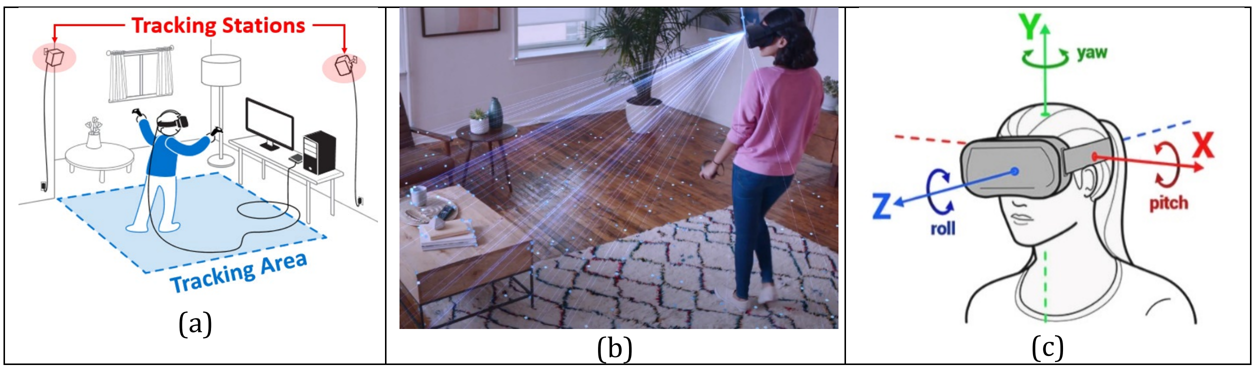

Figure 2: Tracking solutions for HMDs: (a) tracking stations; (b) Visual SLAM; and (c) gyroscopes. Figure a was modified from https://www.vive.com/nz/support/vive/category_howto/verifying-your-setup.html; Figure b was modified from https://www.youtube.com/watch?v=nrj3JE-NHMw; Figure c was modified from https://www.veative.com/blog/gyroscope-important-virtual-reality;

CAVEs use projectors which are directed to between one and six of the walls of an empty room. Each wall receives polarised images from two projectors. By wearing 3D (polarised) glasses, users can perceive only one of the two images with each eye, whichgives users a sense of depth. CAVEs allow the tracking of the user movement by using infrared or ultrasound. Tracking sensors can be attached to the 3D glasses or on an ad-hoc head tracking device.

AR experiences can be generated using two options: Video-See-Through (VST) and Optical-See-Through (OST) devices. Today (2020), VST AR is the most widespread as this can be achieved by using devices like smartphone and tablets. In this case, the device cameras capture live video feeds, which are processed by the device to add AR content and then shown on the screen of the device (see Figure 1). OST AR is achieved by using a (semi-) transparent HMD. As such, users can still see the real world thought the lenses while the digital contents are projected on these lenses. One of the main challenges for AR devices is tracking the position of the devices in the real world in order to determin what the users are looking at. Two solutions have been used to solve this challenge using markers or using marker-less systems. By using markers, the device is programmed to search for pre-defined markers which are the reference point for the AR experience; this is generally done by using QR codes, as shown in Figure 3.a. In the second case, the devices use multiple sensors such as traditional cameras and infrared-deep cameras. The data are then processed using SLAM and Structure from

Motion algorithms to identify the position of the device using references points and triangulation (see Figure 3.b).

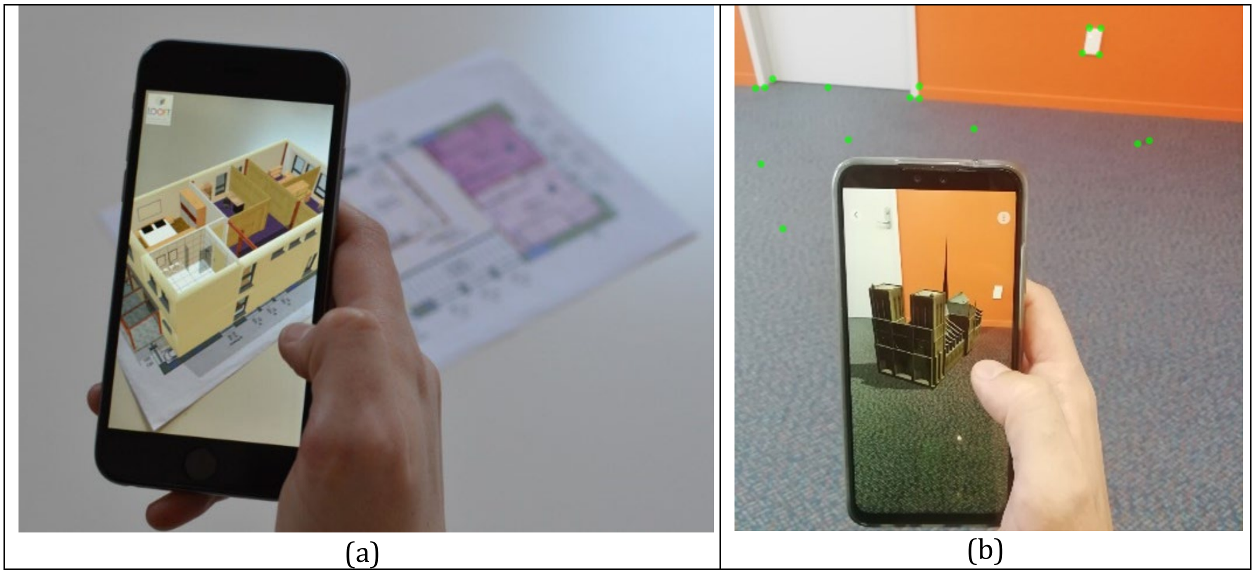

Figure 2: Examples of (a) a marker-based AR application and (b) a markerless AR application (the green dots are the references points identified by the application in the real space). Figure a was modified from https://www.architectmagazine.com/technology/products/three-augmented-and-virtual-reality-apps-for-design-and-construction_o

3.METHODS

AR and VR have already been used in several ways to reduce the impact of disasters on human and built environments. To date, there are several review papers showing the potentialities of these technologies focusing on specific goals (e.g. training and human behaviour investigations) or specific disasters (e.g. fire research). Readers can refer to the following papers (Feng, González, Amor, Lovreglio, & Cabrera-Guerrero, 2018; Kinateder, Ronchi, Gromer, et al., 2014; Ruggiero Lovreglio, 2018; Ruggiero Lovreglio & Kinateder, 2020). This section instead aims a highlight the overall fields in which these technologies have been applied.

The work listed in the following review combines some of the works listed in pre-existing reviews (Feng et al., 2018; Kinateder, Ronchi, Gromer, et al., 2014; Ruggiero Lovreglio & Kinateder, 2020) additional works have been identified by using Google Scholar with the following keywords:

Virtual Reality OR *Augmented Reality* AND *Evacuation*
Virtual Reality OR *Augmented Reality* AND *Evacuation Training*

The work selected in this paper met both the following criteria:

(a) An AR or VR application for building evacuation was proposed;
(b) An AR or VR application was tested through experiments.

4.APPLICATIONS

This work provides a list of works proposing AR or VR applications to enhance the safety design of built environments and support disaster safety training. The selected works have been categorised into three groups given their contributions (a) to enhance the safety design of built environments

(Section 4.1); (b) to investigate how people behave during disasters (Section 4.2); and (c) to train people on how to respond to disasters (Section 4.3). It is worth highlining that some of the works have multiples goals and have been mentioned in more than one group.

4.1 Safety System Design

AR and VR provide users with the possibility to visualise new products and ideas before manufacturing them. This feature has been used in many VR studies to test the effectiveness of various existing or innovative safety systems. Table 1 highlights that most of these studies used a wide range of VR hardware setups and that only a single study compared the results generated by two different types of hardware setups, i.e. VR-CAVE vs VR-HMD (Enrico Ronchi, Mayorga, Lovreglio, Wahlqvist, & Nilsson, 2019). The result also shows that all the works were focusing on fire disasters: building fires, tunnel fires, and underground fires. The design aim of these studies was to enhancement or testing of several safety systems such as exist portals, exit signs, wayfinding systems and other types of signage. Table 1 indicates that there are also multiple studies which used AR to test new wayfinding solutions based on holograms. These holograms were designed to guide evacuees towards the safest and/or the closest exit. A single AR study instead shows how AR can be used to visualise the results of evacuation simulations in existing buildings. Finally, the list of AR studies shows that only one studies tested the potentialities of OST devices, while the remaining works used only VST devices.

Table 1: List of works using AR and VR to enhance the safety design of built environments. Refer to Section 2 for the definitions of hardware setting.

Reference	**Hardware setup**	**Type of Disaster**	**Design Aim**
(E. Ronchi et al., 2016)	VR-CAVE	Tunnel fire	Exit portals
(Cosma, Ronchi, & Nilsson, 2016)	VR-HMD	Tunnel fire	Way-finding systems
(Arias, La Mendola, et al., 2019)	VR-HMD	Tunnel fire	Way-finding systems
(Enrico Ronchi et al., 2019)	VR-CAVE VR-HMD	Road tunnel fire	Exit portals
(Olander, Ronchi, Lovreglio, & Nilsson, 2017)	VR-Non immersive	Building fire	Dissuasive exit signs
(Enrico Ronchi, Nilsson, Modig, & Walter, 2016)	VR-Non immersive	Tunnel fire	Message sign designs
(Mossberg, Nilsson, & Wahlqvist, 2020)	VR-HMD	Underground station fire	Way-finding systems and elevator signs
(Andrée, Nilsson, & Eriksson, 2016)	VR-CAVE	Building fire	Way-finding systems
(Kinateder, Warren, & Schloss, 2019)	VR-HMD	Building fire	Exit signs
(Tang, Wu, & Lin, 2009)	VR -Non immersive	Building fire	Way-finding systems
(Occhialini et al., 2016)	VR -Non immersive	Building fire	Exit signs
(Kostakos et al., 2020)	VR-HMD	Underground parking lot fire	Way-finding systems
(Duarte, Rebelo, Teles, & Wogalter, 2014)	VR-HMD	Explosion/fire	Safety signs

(Lochhead & Hedley, 2018)	AR-VST	General evacuation	Building Evacuation design
(Ahn & Han, 2012)	AR-VST	General evacuation	Way-finding systems
(Tsai & Yau, 2013)	AR-VST	Radioactive accidents	Way-finding systems
(Ortakci, Atila, Demiral, Ozacar, & Karas, 2017)	AR-VST	Building fire	Way-finding systems
(Stigall & Sharma, 2017)	AR-VST	Building fire	Way-finding systems
(Diao & Shih, 2018)	AR-VST	General evacuation	Way-finding systems
(Mitsuhara, Tanimura, Nemoto, & Shishibori, 2019)	AR-VST	General evacuation	Way-finding systems
(Kitamura, Yasui, & Nakatani, 2019)	AR-VST	General evacuation	Way-finding systems
(Catal, Akbulut, Tunali, Ulug, & Ozturk, 2019)	AR-VST	General evacuation	Way-finding systems
(Cai, Yang, & Tao, 2018)	AR-OST	General evacuation	Way-finding systems

4.2 Human Behaviour Investigation

In the last two decades, VR has been proved to be a powerful tool to immerse people in different scenarios and to investigate how they behave in these scenarios. It has also been used in safety research to investigate how people would behave in different disasters. Table 2 shows that the great majority of existing studies have been carried out to investigate human behaviour in fire scenarios. However, VR has also been used in few cases for behavioural investigation for earthquakes, wildfires and floods. It is also possible to highlight that VR studies mainly focused on the investigation of exit and/or route choices while a few studies investigate evacuee navigations and other evacuation behaviours. No AR study was identified for human investigations in disasters.

Table 2: List of works using AR and VR to investigate human behavior in disasters. Refer to Section 2 for the definitions of hardware setting.

Reference	**Hardware setup**	**Type of Disaster**	**Behaviors under investigation**
(Lin, Zhu, Li, & Becerik-Gerber, 2020)	VR-HMD	Underground station fire	Exit/Route choice
(Zhu, Lin, Becerik-Gerber, & Li, 2020)	VR-HMD	Underground station fire	Exit/Route choice
(Wetterberg, Ronchi, & Wahlqvist, 2020)	VR-HMD	Wildfire	Driving behavior
(Cao, Lin, & Li, 2019)	VR-HMD	Building fire	Exit/Route choice
(Kinateder et al., 2015)	VR-CAVE	Tunnel fire	Exit/Route choice
(Kinateder & Warren, 2016)	VR-HMD	Building fire	Pre-evacuation
(Kobes, Helsloot, de Vries, & Post, 2010)	VR-Non immersive	Building fire	Exit/Route choice and pre-evacuation
(Tucker et al., 2018)	VR-Non immersive	Building fire	Exit/Route choice

(Kinateder, Müller, Jost, Mühlberger, & Pauli, 2014)	VR-CAVE	Tunnel fire	Exit/Route choice
(Feng, González, Trotter, et al., 2020)	VR-HMD	Earthquake	Exit/Route choice and pre-evacuation
(Bourhim & Cherkaoui, 2020)	VR-HMD	Building fire	Pre-evacuation and response behaviours
(Kinateder, Ronchi, Gromer, et al., 2014)	VR-CAVE	Tunnel fire	Exit/Route choice
(Kinateder, Comunale, & Warren, 2018)	VR-HMD	Building fire	Exit/Route choice
(Arias, Nilsson, & Wahlqvist, 2020)	VR-HMD	Building fire	Pre-evacuation and
(Arias, Fahy, et al., 2019)	VR-HMD	Building fire	Pre-evacuation
(Enrico Ronchi et al., 2015)	VR-CAVE	Tunnel fire	Exit/Route choice
(Andrée et al., 2016)	VR-CAVE	Building fire	Exit/Route choice and waiting time at the elevator
(Shih, Lin, & Yang, 2000)	VR-Non immersive	Building fire	Exit and route choice
(Shih et al., 2000)	VR-Non immersive	Building fire	Exit/Route choice
(Fujimi & Fujimura, 2020)	VR-HMD	Flood	Pre-evacuation
(Aleksandrov, Rajabifard, Kalantari, Lovreglio, & González, 2018)	VR-Non immersive	Building fire	Exit/Route choice
(Meng & Zhang, 2014)	VR-Non immersive	Building fire	Exit/Route choice
(Drury et al., 2009)	VR-Non immersive	Underground station fire	Navigation and other behavious
(R. Lovreglio, Ronchi, & Nilsson, 2015)	VR-CAVE	Tunnel fire	Navigation
(Ruggiero Lovreglio et al., 2014)	VR-Non immersive	Building fire	Exit/Route choice
(R Lovreglio, Fonzone, & Dell'Olio, 2016)	VR-Non immersive	Building fire	Exit/Route choice

4.3 Disaster Safety Training

AR and VR have great potentialities for training purposes in different fields. This also applies to the fire safety research as several VR and AR applications have been proposed to train people for several disasters such as earthquakes, tsunamis, tornados, aircraft accidents and building fires. Table 3 indicates that a high heterogeneity of hardware setups for both VR and AR studies, and it shows that several studies have investigated the use of multiple setups. Most of the listed studies have been used to teach people multiple skills on how to cope with a disaster while there are some studies focusing on specific safety tasks such as the use of fire extinguishers.

Table 3: List of works using AR and VR to train people on how to respond to disasters. Refer to Section 2 for the definitions of hardware setting.

Reference	Hardware setup	Type of Disaster	Training Goals
(Feng, González, Mutch, et al., 2020)	VR-HMD	Earthquake	Earthquake preparedness
(Mitsuhara & Shishibori, 2020)	VR-HMD AR- VST	Tornado	Tornado awareness
(Li, Liang, Quigley, Zhao, & Yu, 2017)	VR-HMD	Earthquake	Drop cover and hold
(Ruggiero Lovreglio, Duan, Rahout, Phipps, & Nilsson, 2020)	VR-HMD	Building fire	Use of fire extinguishers
(Månsson & Ronchi, 2018)	VR-HMD	Building fire	Use of fire extinguishers
(Feng et al., 2019)	VR-HMD	Earthquake	Earthquake preparedness
(Burigat & Chittaro, 2016)	VR-HMD	Aircraft accident	Location of emergency exits
(Chittaro & Buttussi, 2015)	VR-HMD	Aircraft accident	Brace position and evacuation procedures
(Smith & Ericson, 2009)	VR-CAVE	Building Fire	Fire evacuation procedures
(Kinateder et al., 2013)	VR-CAVE	Tunnel Fire	Fire safety behaviors
(Farra et al., 2019)	VR-Non immersive VR- HMD	Building Fire	Evacuation of neonates
(López, Plá, Méndez, & Gervás, 2010)	AR-VST	Building Fire	Fire evacuation procedures
(Kawai, Mitsuhara, & Shishibori, 2016)	AR-VST	Tsunami and earthquake	Evacuation procedures
(Mitsuhara, Shishibori, Kawai, & Iguchi, 2016)	AR-VST	Tsunami	Evacuation procedures
(Mitsuhara, Iguchi, & Shishibori, 2017)	AR-VST AR-OST	Earthquake	Earthquake preparedness
(Mitsuhara, Iwaka, et al., 2017)	AS-VST	Tsunami and earthquake	Evacuation procedures
(Sharma, Bodempudi, Scribner, Grynovicki, & Grazaitis, 2019)	AR-VST AR-OST	Building fire	Location of emergency exits

DISCUSSION AND CONCLUSION

This work provides an overview of the existing Augmented Reality (AR) and Virtual Reality (VR) hardware setups which can be used for research related to human behaviour in disasters (see Section 2). Moreover, it provides a review of applications which have been developed in the last decades to enhance the safety of humans when facing disasters (see Section 4). The review has identified 64 works that have investigated the potentiality of AR and VR for three main goals: (a) enhancing the safety design of built environments; (b) investigating human behaviour; (c) training people.

This work shows that researchers have a vast set of options of hardware setups that they can use to carry on research on human behaviour in disasters. The selection of the optimal setup depends on several factors such as research budget and research goals. For instance, some VR and AR setups, such as VR-CAVE and AR-OST, are still very expensive when compared with alternative VR and AR hardware setups. When selecting a hardware setup, it is always worth considering that options listed in Section 2 can generate different level of immersion for users and interactions with the digital elements. Table 1, 2 and 3 identify only a few studies that have compared the research output generated while using different VR and AR setups to investigates the same research question, for instance (Farra et al., 2019; Enrico Ronchi et al., 2019) for VR setups comparisons and (Mitsuhara, Iguchi, et al., 2017; Sharma et al., 2019) for AR setups comparisons. Although these works provide preliminary results on how different setups works and their advantages and limitations, it is necessary to gather more evidence with future studies. To date, there is only one study that have tested both VR and AR solutions to enhance disaster awareness (Mitsuhara & Shishibori, 2020).

The review illustrates that there are 23 studies used VR and AR to enhance the safety design of built environments. This was done by either asking participants to compare and rate different layouts or by observing how people behaved while exposed to different layouts. The review indicates that VR studies only focused on fire disasters, and there is still the need to investigate whether similar approaches can be used to investigate safety systems for other types of disasters. AR studies have shown the benefit of using a hologram guide system to help evacuees selecting the right route and exit. However, there is only one study that investigated the potentiality of AR-OST devices. This is probably due to the lack of these devices in the past years and their expensive costs. However, with the recent release of new AR-OST devices, there is the expectation of having more applications and studies using AR-OST in the coming years (Ruggiero Lovreglio & Kinateder, 2020).

The review also highlights that different VR solutions have been widely used to investigate how people behave in disasters such as building fires, earthquakes and wildfires. However, one of the main concern is the ecological validity (i.e. whether the people shows similar behaviour in VR and real disaster) of the data collected using VR (Kinateder, Ronchi, Nilsson, et al., 2014). To date, there are already a few studies that have tried to provide an answer to this fundamental question, see for instance the following reference (Arias, Fahy, et al., 2019; Feng, González, Trotter, et al., 2020; Kinateder & Warren, 2016). However, there is a need for more studies comparing real and virtual studies to have a quantitative assessment of the ecological validity of VR investigations. The review also shows that there is no AR study focusing on the investigation of human behaviour in disasters. However, there are a lot of potentialities for AR investigations, as discussed in (Ruggiero Lovreglio & Kinateder, 2020).

Finally, this review shows that VR and AR have been used to train people for many disasters in 18 studies. These studies show the versatility of these technologies as they have been used to train people for very different disasters. One of the key questions regarding training is if VR and AR training solution can perform better than traditional training solutions. Today, several studies have been trying to answer this questions for different VR solutions see for instance (Chittaro & Buttussi, 2015; Kinateder et al., 2013; Ruggiero Lovreglio et al., 2020). The preliminary finding of these works shows several advantages of using VR for safety training especially when focusing on the knowledge retention (i.e. how much people remember after weeks from the training). To date, there is no study comparing AR training with traditional training; however, it is arguable to expert results similar to the VR studies.

In conclusion, this work shows that several studies have been carried out using VR and AR for human behaviour in disasters. The review shows that most of these works have been focusing on fire disasters, especially for safety design and behavioural investigations. The review shows that there is a need for more studies comparing the pros and cons of different VR and AR hardware setups and to validate the results obtained using these new emerging technologies.

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