Augmented Reality for Pedestrian Evacuation Research: Promises and Limitations

Lovreglio R[1] & Kinateder M[2]

[1] School Built Environment, Massey Univeristy, New Zealand
[2] National Research Council Canada, Canada

Abstract: Evacuation effectively mitigates potential harm for building occupants in case of emergencies. Virtual and Augmented Reality (VR and AR) have emerged as research tools and means to enhance evacuation preparedness and effectiveness. Unlike VR, where users are immersed in computer-generated environments, the more novel AR technology allows users to experience digital content merged into the real world. Here, we review current (2019) relevant literature on AR as a tool to study and improve building evacuation triggered by a variety of disasters such as fires, earthquakes or tsunami. Further, we provide an overview of application goals, existing hardware and what evacuation stages can be influenced by AR applications. Finally, we discuss strengths, weaknesses, and opportunities (SWOT) of AR to study evacuation behaviour and for research purposes.

Keywords: Building Evacuation; Augmented Reality; Disasters; Hardware; software; SWOT analysis

1. Introduction

Evacuation is a key risk-reduction strategy for buildings threatened by disasters (Bernardini, D'Orazio, & Quagliarini, 2016; Watts & Hall, 2016). To better understand how people evacuate buildings, a range of scientific observation and simulation techniques have been developed. These include announced and unannounced drills, case studies, laboratory experiments and computational models (Bernardini, Lovreglio, & Quagliarini, 2019; S. M. V. Gwynne et al., 2017; R. Lovreglio, Kuligowski, Gwynne, & Boyce, 2019; Nilsson, 2009). These techniques have provided insights into human behaviour in disasters such as fire and earthquakes and helped to progress the simulation of human behaviour using several modelling solutions (Steve M. Gwynne, Galea, Owen, Lawrence, & Filippidis, 1999; Erica D. Kuligowski, Peacock, & Hoskins, 2010; Lindell & Perry, 2012; R. Lovreglio et al., 2017).

Emerging technologies like Virtual and Augmented Reality (VR and AR) have generated interest in the greater safety research community in recent years. Two key expectations have fueled this trend (Max Kinateder et al., 2014; Le et al., 2015; X. Li, Yi, Chi, Wang, & Chan, 2018). First, VR and AR could provide effective, flexible and affordable training platforms for safety-relevant scenarios. Second, VR and AR could balance ecological validity and experimental control in research studies. Much has been written about VR as a tool to investigate human behaviour and train people for emergency scenarios (Y. Feng, Duives, Daamen, & Hoogendoorn, 2019; Z. Feng, González, Amor, Lovreglio, & Cabrera-Guerrero, 2018; Max Kinateder et al., 2014; Max Kinateder, Wirth, & Warren, 2018; H. Li, Zhang, Xia, Song, & Bode, 2019; Ruggiero Lovreglio, Duan, Rahout, Phipps, & Nilsson, 2020; Nilsson & Kinateder, 2015). AR, however, has only recently been identified as a training and research tool in *pedestrian evacuation research*. AR has received considerable attention in related fields (e.g., construction and industrial safety), and a recent review article identified potential applications and associated challenges of the method (X. Li et al., 2018; Potts, Sookdeo, Westerheide, & Sharber, 2019). Here, we review existing AR applications for evacuation research, identify use cases, and highlight challenges for developers of AR applications in our field. Further, we discuss we discuss strengths, weaknesses, opportunities, and threats (SWOT) of AR as a training and research tool.

1.1 Augmented Reality

AR and VR have been gaining popularity with the release of mobile consumer hardware and software in recent years. Both technologies are used to present virtual content to users but differ in the degree of how virtual content is intertwined with the real world. In VR, the user experience is completely synthetic as all content presented is virtual. Typically, content is shown via stereoscopic displays that can either be worn on the head (so-called Head-Mounted Displays), via large screens or projection technologies. In AR, part of the content is virtual and can either be 2D (e.g., presenting text information in the foreground of a screen) without any interaction with the spatial structure of the real world, or 3D (e.g., presenting a virtual object so that it appears to be placed on a real-world object) with consideration of the spatial structure (Carmigniani et al., 2011)[1]. As of 2019, well-known examples include Glass (Google), HoloLens (Microsoft) and the popular smartphone application Pokemon Go (Niantic).

More than twenty years ago, Milgram and Kishino defined a conceptual framework describing AR and VR (Milgram & Kishino, 1994). The *virtuality continuum* places real and virtual environments at opposite poles. At one end of this continuum are environments consisting solely of real objects (i.e., a person only sees the real world). At the other hand, we have environments consisting solely of computer-generated objects (i.e., a person only sees a virtual world). Mixed Reality environments are combinations of real and virtual content and placed in the centre of the continuum. Augmented Virtuality (AV) describes predominantly virtual environments with some real-world content. In AR environments, the main component is reality, while the computer-generated visual information is a secondary component (Figure 1).

The technological differences between AR and VR hardware influence the type of (training) applications. In VR, users can train in completely computer-generated environments, thus enabling access to theoretically endless numbers of training scenarios and training contexts. Since the virtual content is embedded in the real world in AR applications, training options are slightly different. For instance, training can be more tailored to specific contexts (e.g., where are emergency exit signs placed in my specific building?).

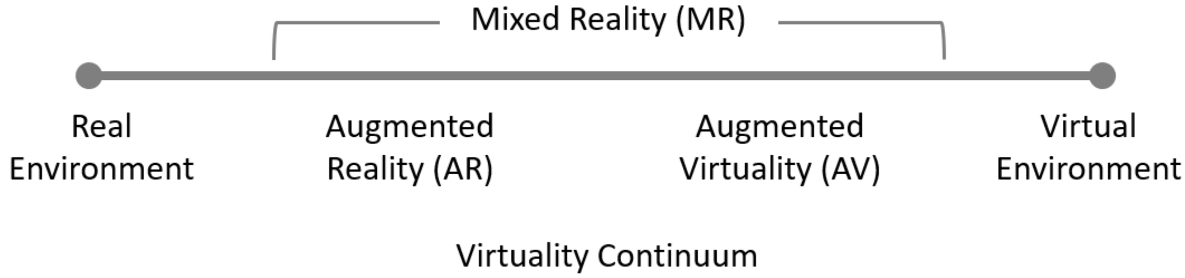

Figure 1 – Virtuality continuum (Milgram & Kishino, 1994)

AR content can be presented via a variety of devices, which have noticeable differences in how content is displayed, and how the display device is worn. The most widespread AR technology today are probably handheld mobile *video-see-through (VST)* devices such as smartphones (see Figure 2.a). In video-seethrough AR, cameras capture live video feeds, which are processed to add AR content and then shown in de facto real-time on an opaque screen. The premise of this approach is that the integration of AR features into affordable and widely used consumer AR systems will broaden the impact of this technology. Evacuation related examples of this technology are smartphone applications that could guide building occupants to a place of safety during emergencies. This can be achieved by projecting information about usable egress routes over a video feed of the real world (Ahn & Han, 2011, 2012; Mitsuhara, Shishibori, Kawai, & Iguchi, 2016). There are also video-see-through head-mounted devices, but these are still less widespread and typically require custom-built hardware combining traditional head-mounted headsets (e.g. Rift CV2 and Quest, Oculus) with stereoscopic cameras (e.g. ZED mini camera).

Head-mounted *optical-see-through (OST)* devices can augment vision without having to cover the eyes with an opaque screen (see Figure 2.b). Here, users are typically wearing a (semi-) transparent HMD. That is, users still see the real world with additional virtual content projected into it. As of 2019, optical-see-through Head-Mounted Displays have still not penetrated the mass consumer market, but several commercial products, such as HoloLens (Microsoft, Redmond, WA), One (Magic Leap, Plantation, FL) and Glass (Google, Mountain View, CA), have been released. These new products are benefitting from the cost-savings of mass production, increased computational power, enhanced form factor, and – maybe most importantly – the relative ease to develop software applications for them. These devices trade-off un-occluded natural vision provided by the OST display for lower contrast, limitations in colour display, and – to this date – a relatively small field of view compared to VST Head-Mounted Displays. Some studies have used optical-see-through AR for disaster management (Asgary, 2017) and general spatial navigation (Wang et al., 2018). A few studies leveraging this technology specifically as a training

[1] It is worth highlighting that other definitions have been used. For instance, other definitions augmented reality allows the visualization of only 2D digital contents while mixed reality allows an integrated visualization of 3D digital contents and reality.

tool for disaster evacuation have been published (Kawai, Mitsuhara, & Shishibori, 2016a; Mitsuhara, Iguchi, & Shishibori, 2017).

AR applications must solve two problems: tracking and recognizing. An AR application needs to know where the user and the device are in the environment and track their movement. It also needs to know what the user is looking at; i.e. an understanding of the spatial properties (e.g., the shape of the room, location of objects) needs to be reconstructed. The tracking can be accomplished using markers (e.g. Quick Response codes placed in the environment) or using marker-less systems (e.g., using sensors built into the device; see Figure 3). In the first case, the algorithms constantly search for pre-defined markers to impose digital elements using those markers as reference points. In the second case, more advanced techniques, such as Simultaneous Localization And Mapping (SLAM) and Structure from Motion are used for mapping fiducial markers to estimate relative positions (Carmigniani et al., 2011). A review of AR tracking, interaction and display solutions is available in (Feng Zhou, Duh, & Billinghurst, 2008; Wagner & Schmalstieg, 2009).

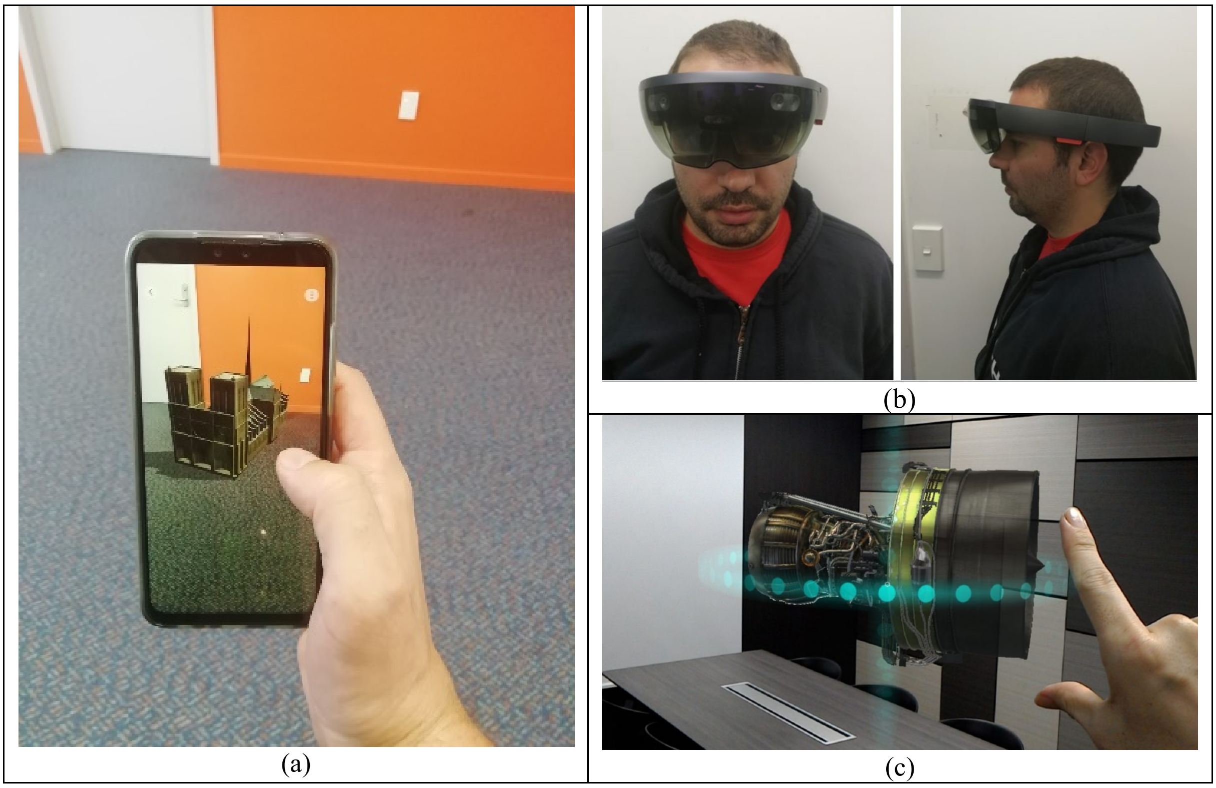

Figure 2 – Example of (a) a video-see-through (VST) device and (b) an optical-see-through (OST) device and (c) its user view (Microsoft, 2016).

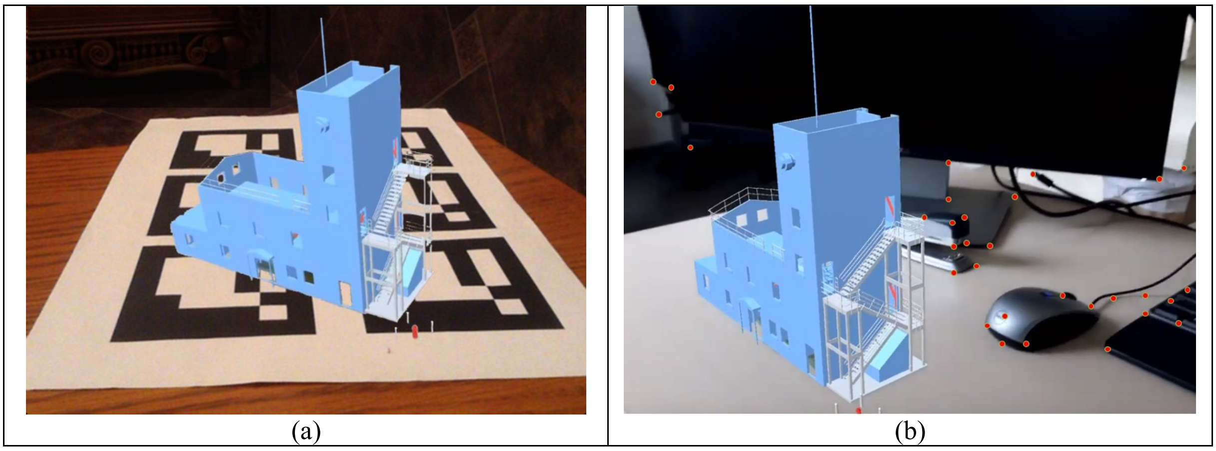

Figure 3 – Example of (a) a marker-based AR application and (b) a markerless AR application (in red the fiducial markers identified in the scene). This figure shows an educational application developed in Unity by the first author.

1.2 AR for Building Evacuation

Before discussing AR applications for building evacuation, it is worth describing the timeline characterising evacuations. The time required to complete a building evacuation is known in the literature as the required safe egress time (RSET). This time needs to be smaller than the available safe egress time (ASET), which is the time available to evacuate a building safely before the building conditions become untenable for occupants (S. M. V. Gwynne & Boyce, 2016; E.D. Kuligowski, 2016). RSET can be divided into several subsequential time periods as shown in Figure 4. Each step in the timeline needs to be completed for a successful evacuation.

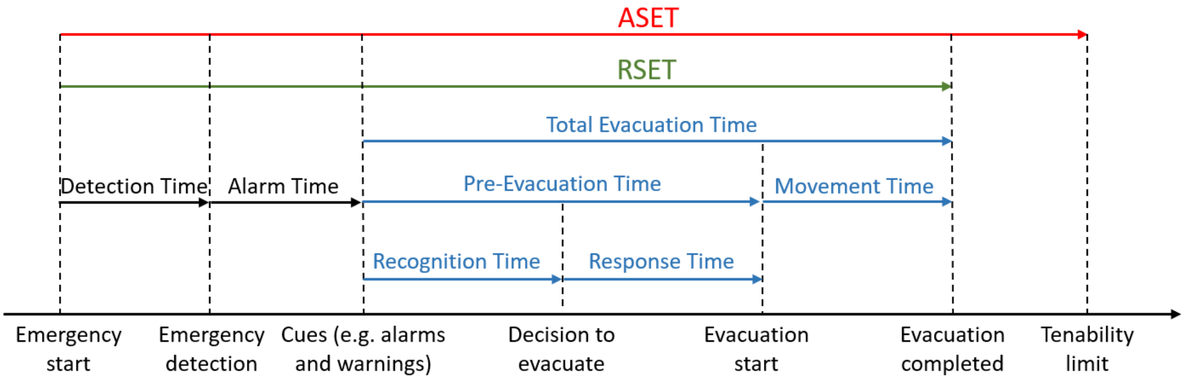

Figure 4 – Timeline building evacuation framework (Erica D Kuligowski, 2016). Figure source: (Ruggiero Lovreglio, 2016)

Total evacuation time accounts for all human behaviour in an emergency, beginning when occupants receive first cues (e.g., the sound of an alarm), and ending when the evacuation has been completed. For some types of disasters, such as fire and wildfires, the pre-evacuation stage can be a bigger component of total evacuation time. Building occupants need time to recognise the emergencies and prepare for the actual evacuation (Ruggiero Lovreglio, Kuligowski, Gwynne, & Strahan, 2019; Ruggiero Lovreglio, Ronchi, & Nilsson, 2015, 2016). For other disasters, such as earthquakes, building occupants can easily recognise the threat (R. Lovreglio et al., 2017). The final stage of a building evacuation comprises the actual movement towards safety.

AR can be used to investigate human behaviour and train building occupants in different evacuation stages. To date, several reviews are available in the literature investigating different evacuation purposes of VR tools; see, for instance (Z. Feng et al., 2018; Max Kinateder et al., 2014). However, a comprehensive literature review of AR applications for building evacuation is still not available. The present work aims at covering this gap.

2. Systematic Literature Review

2.1 Review Objective

We defined the following four objectives for a systematic review of literature on AR applications for pedestrian evacuations in indoor and outdoor built environments. Our goal was to identify the …

1. … disasters in which AR applications have been used;
2. … evacuation stages targeted by AR applications;
3. … hardware and software used for AR applications;
4. … comparison between AR solutions and comparison between AR and traditional solutions.

2.2 Work Selection

We collected papers from journals, conferences, patents and reports. We recovered papers from the following databases: Google Scholar, Scopus and IEEE Xplore. To be included, literature needed to address two major concepts: augmented reality and building evacuation. We used the following combination of keywords: *augmented reality* OR *smart glasses* OR *HoloLens* + *evacuation*. We included only works written in English in the first search. We ran the search in August 2019 and selected 31 out of 300 publications accessed through Scopus, Google

Scholar and. This first filtering process was based on the presence of the selected keywords in the title and abstract of the initial sample.

We ran a second filtering process, considering the following two selection criteria:

(a) An AR application for pedestrian evacuation was proposed;
(b) An AR application was tested empirically.

We identified 23 papers meeting at least one of the two criteria. The full selection process described in this section is illustrated in Figure 5.

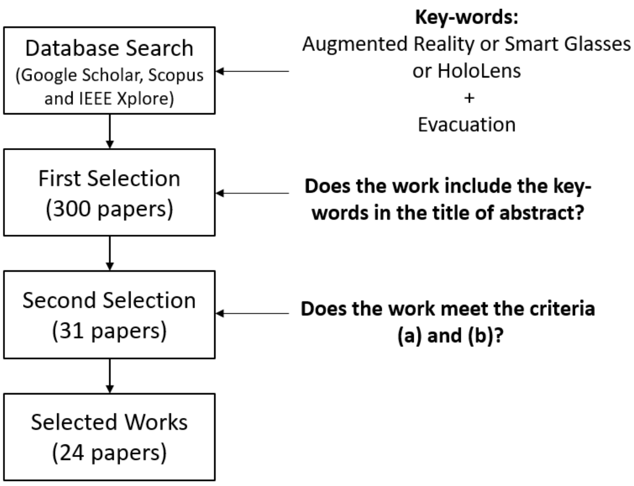

Figure 5 – Selection process for the review.

3. Results

Table 1 shows a list of the selected 23 papers. We aggregated the papers into 18 case studies, as several papers were presenting similar aspects of the same AR application. All selected papers were published between 2010 and 2019, showing that applications of AR for building evacuation are recent research goals. In addition, Figure 6 illustrates that there is a growing trend within this period. This trend can be explained by the increase of hardware and software options to develop AR applications (e.g., MS HoloLens and its developer toolkit were released in 2016) as highlighted in previous work (X. Li et al., 2018).

Table 1 and Figure 7 highlight that most AR applications do not focus on any specific type of evacuation and are of general purpose. The remaining applications were instead developed focusing on specific type of disasters: tsunami, earthquake, fire, and radioactive accidents. Finally, Table 1 indicates that many AR applications (33%) were tested in university buildings (and thus most likely used student samples) and were in prototyping stages. Several other applications were tested in different buildings, such as schools, large-scale buildings, or outdoor built environments.

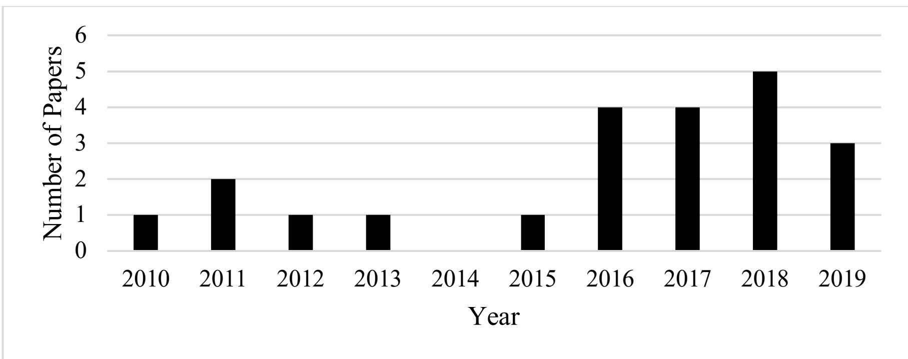

Figure 6 – Number of papers included in the systematic review by year. Note: the data related to 2019 are partial as the review was carried out in August 2019)

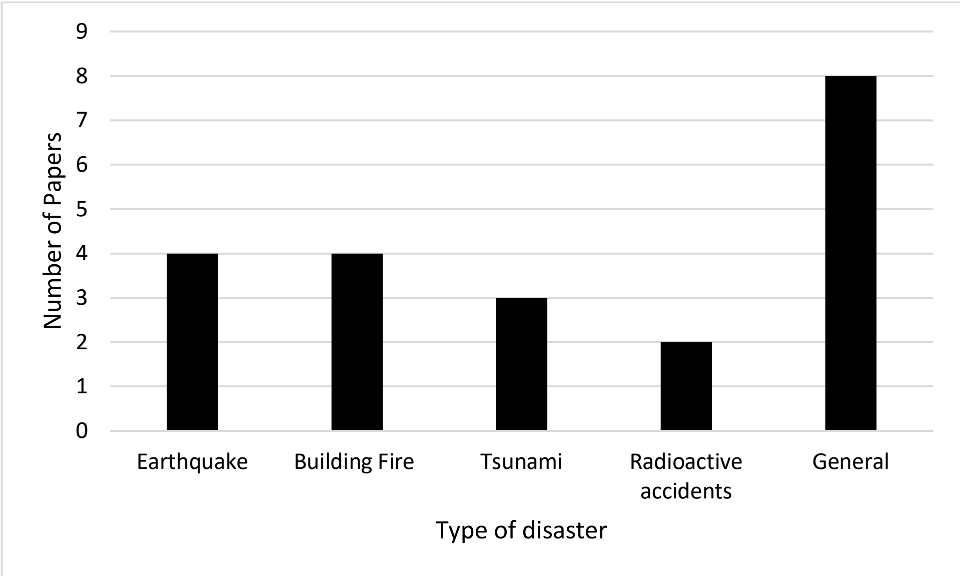

Figure 7 – Number of papers included in the systematic review by type of disasters for the AR applications.

3.1 Application Goals

Through this review, we identified three types of goals for AR applications: training, navigation support, and visualisation of evacuation simulations. Most applications (8 case studies) were developed for *training purposes*. Those applications were conceived to overcome some of the well-known limitations of traditional evacuation drills which are highlighted by Gwynne *et al.* (2016, 2017) and Amos *et al.*, (2019). These limitations include the lack of realism of evacuation drills, individual feedback, or inclusion of scenarios (e.g., inability to use the standard egress route). Kawai et al. (2016a) López et al. (2010) augmented drills by visualizing fire, smoke, injured occupants, and cracks generated by an earthquake and building fire. Mitsuhara *et al.* (2017) augmented their AR training tool By showing the impact of an earthquake on a building and other people. Iguchi, Mitsuhara and Shishibori (2016) as well as Mitsuhara, Iguchi and Shishibori (2017) enhanced the realism of their earthquake drills by visualizing earthquake damage as well as interactive virtual human agents.

Gamification, i.e., adding elements to an application that are typically found in computer games (e.g., scoring points, competition with others, rules of play) is an approach that could increase training effectiveness. For instance, individualized feedback was discussed in two works: Mitsuhara *et al.* (2017) used a scoring system which rises and falls depending on the choices made by the users during a simulated drill. A similar approach was also proposed by Mitsuhara, Iguchi and Shishibori (2017) as a possible step forward to add more gamification in their earthquake AR training tool. Another example was developed by Catal *et al.* (2019) who report on a game-based mobile application that trains users to evacuate via the nearest emergency exit in case of fire or other emergencies.

Another popular type of AR application goal is to support *building occupants navigate* during indoor (7 case studies) or outdoor evacuations (2 case studies). The indoor navigation AR applications identified in this review can be subdivided into three groups which provide wayfinding information using different approaches. The first type of applications supports the navigation of evacuees by showing them the direction to go through using AR arrow and exit sign tags displayed on tablets and smartphones (Figure 8). This solution was proposed originally in a patent (Yi-Wen Cai & Shih-Cheng Wang, 2011). Variations of this idea were published for pathfinding in high (Ahn & Han, 2012; Cai, Yang, & Tao, 2018) and low visibility conditions (Diao & Shih, 2018). The second type of applications augments the evacuation plan by showing a 3D visualization of the floor where the evacuees are located (Figure 9). This solution helps the understanding of where a person is and where they need to go to evacuate (I. Lochhead & Hedley, 2018; Stigall & Sharma, 2017). The third approach consists of a hybrid solution using a mirror signage and AR animations visualized on a projector screen as illustrated in Figure 10. In this case, information is provided by humanoid AR animations indicating the evacuees the direction to take (Kitamura, Yasui, & Nakatani, 2019).

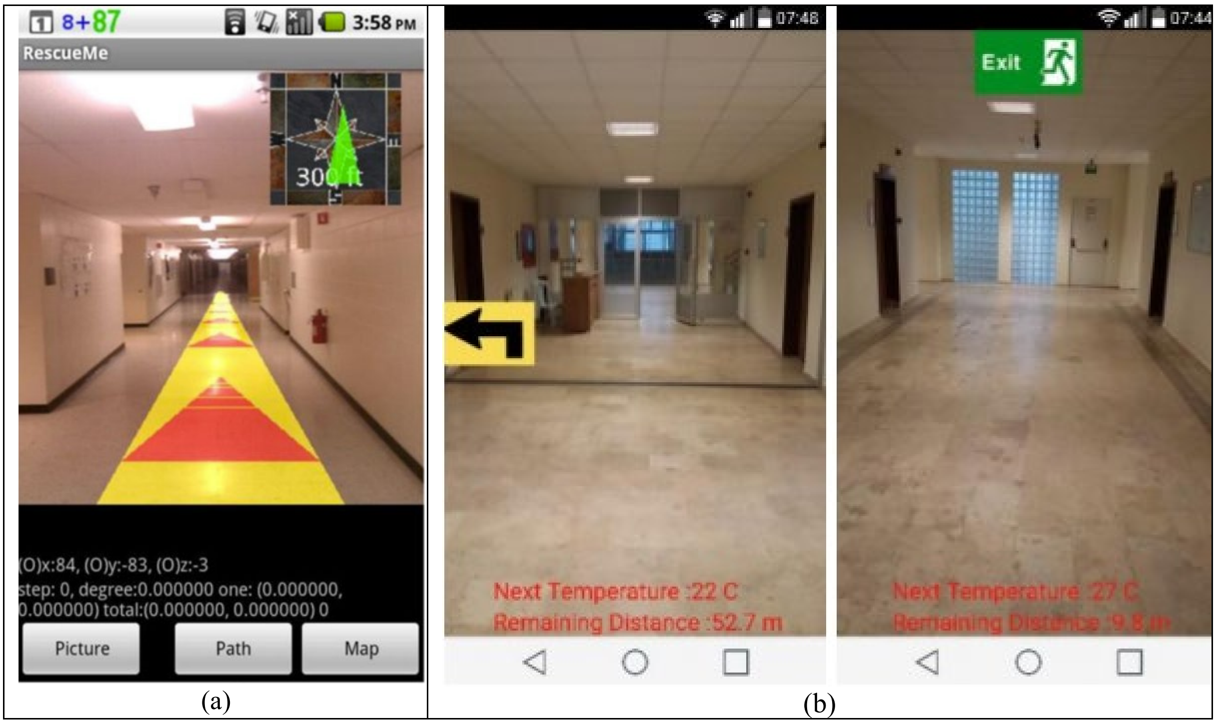

Figure 8 – Examples of AR arrow and exit sign tags: (a) RescueMe (Ahn & Han, 2012) and (b) the smart evacuation system proposed by (Ortakci, Atila, Demiral, Ozacar, & Karas, 2017). Figures reproduced with permission.

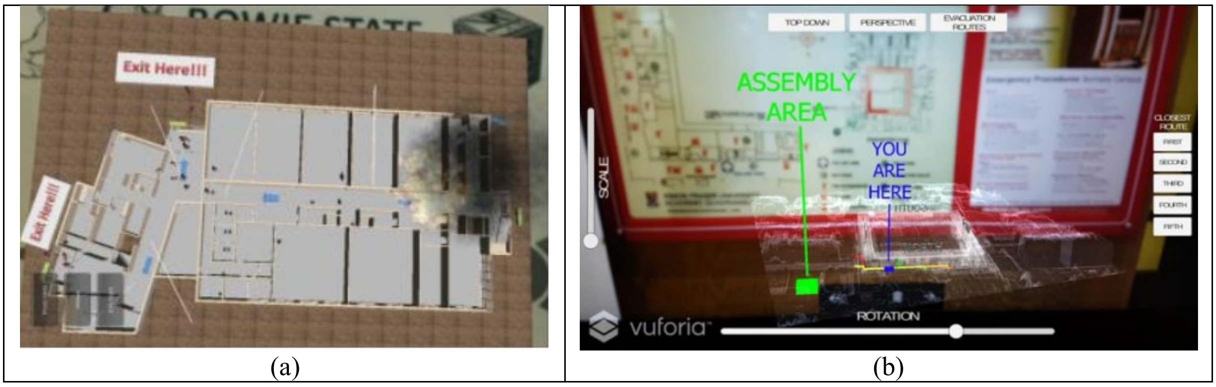

Figure 9 – Example of AR visualization of evacuation plans: (a) solution proposed in (Stigall & Sharma, 2017); and (b) solution proposed in (I. Lochhead & Hedley, 2018). Figures reproduced with permission.

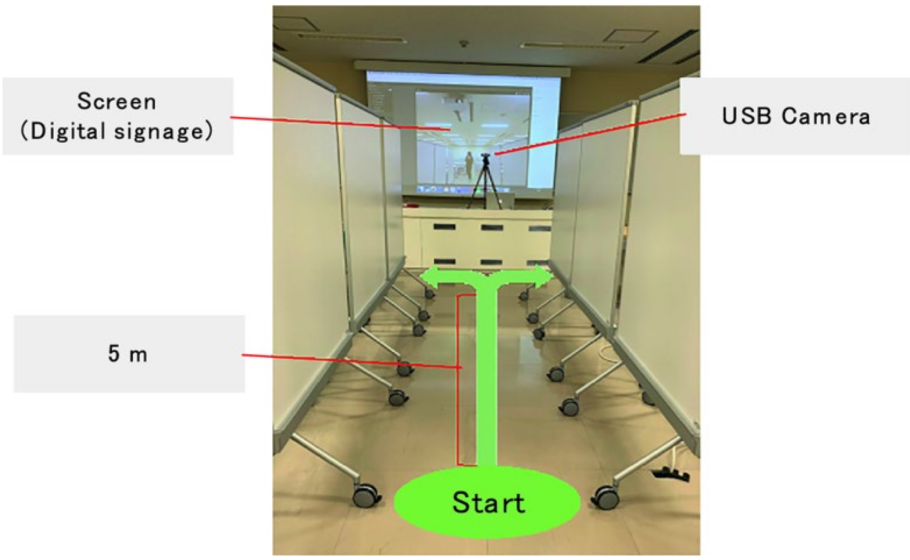

Figure 10 – The mirror signage and AR animation system proposed in (Kitamura et al., 2019). Figure reproduced

with permission.

The outdoor navigation AR applications proposed by Tsai and Yau (2012, 2013) aims at providing real-time augmented information about radioactive threats and the location of the available shelters in case of nuclear accidents. Mitsuhara *et al.*, (2019) developed another AR application to prompt speedy evacuation by and enhancing the reality with human holograms indicating the direction to go.

Finally, the latest type of application *visualises building evacuation simulations*. This solution was recently developed by Lochhead and Hedley (2018) to investigate if and how AR can be used to evacuee movement simulated by existing evacuation models. As such, they provide a new approach to link evacuation simulations with the real-world context of the built environment.

3.2 Type of Hardware

The AR applications listed in Table 1 were developed using both VST and OST devices. It is worth noting that all applications published before 2016 were VST and used mainly handheld non-immersive devices (e.g., smartphones and tablets) to visualise AR content. However, some authors have tested the effectiveness of immersive VST solutions in Head-Mounted Displays, which stream a real-time video of the environment in front of the users (Kawai, Mitsuhara, & Shishibori, 2016b; Mitsuhara, Iguchi, et al., 2017). Although immersive solutions can enhance the level of perceived realism, Kawai et al. (2016b) reported that they could also produce more motion sickness and discomfort for users compared to handheld devices.

The first publications showing an OST application was published in 2016 (Kawai et al., 2016a; Mitsuhara et al., 2016) and demonstrated the potentials and limitation of smart glasses. In both publications, a small field of view and limited usability were reported to be the main limitations. In more recent years (2018-2019), the most commonly used OST device is HoloLens (Microsoft) which has been tested in three studies (Cai et al., 2018; Saunders et al., 2018; Sharma, Bodempudi, Scribner, Grynovicki, & Grazaitis, 2019). At the time of the current review, the first rendition of HoloLens still has several limitations: mapping update rate (ca. 1Hz); mapping distance; a relatively small field of view (ca. 30º horizontally).

To date, only two studies are comparing the pros and cons of different AR pieces of hardware from a user viewpoint. Mitsuhara, Iguchi and Shishibori (2017) tested and compared Rift (Oculus; PC powered immersive headset), Cardboard (Google; smartphone-powered headset), and Moverio (Epson; smart glasses) for training purposes. After using each system, participants rated usability as well as visual capabilities and found Cardboard to be best. Note, however, that each of the three systems is designed for different purposes and the systems have vastly different capabilities. Sharma *et al.* (2019), instead, compared how users evaluated VST and OST solutions using HoloLens, a tablet and a phone and found that OST solutions were preferred over VST solutions.

Table 1 shows that all the AR application running on handheld devices before 2017 required external markers to track their position and rotation in space. These devices were not capable of handling the Simultaneous Localization And Mapping and Structure from Motion algorithms described in Section 2.1. From 2017 on, the situation changed with studies using a new generation of AR devices and software packages such as ARKit (Apple Inc.) and ARCore (Google). This new hardware and software allow using simplified versions of Simultaneous Localization And Mapping and Structure from Motion algorithms, which are capable to detect flat surfaces and use them as markers. In some cases, tablets and smartphones were used without markers. This was possible using a cloud system locating the devices and providing them with the appropriate digital contents or these devices were using GPS (e.g., for outdoor geolocation).

Regardless of the performance increase of tablets and smartphone, these devices are limited in the type and amount of AR contents that can be visualised at the same time. Stigall and Sharma (2017) reported this issue when they developed and application visualising particle systems and multiple humanoid agents evacuation from a building.

Table 1 - Papers selected for review process.

Case Study	Reference	Disaster	Goal	Type of hardware*	Marker-based	Type of Building	Evacuation Stage
1	(López, Plá, Méndez, & Gervás, 2010)	Fire	Training	Smartphone (VST)	No	General	Movement
2	(Yi-Wen Cai & Shih-Cheng Wang, 2011)	General	Indoor navigation	Smartphone and Tablet (VST)	No	General	Movement
3	(Ahn & Han, 2011) (Ahn & Han, 2012)	General	Indoor navigation	Smartphone (VST)	No	Large scale buildings	Movement
4	(Tsai et al., 2012) (Tsai and Yau, 2013)	Radioactive accidents	Outdoor navigation	Smartphone (VST)	Yes	Outdoor	Movement
5	(Kawai, Mitsuhara, & Shishibori, 2015) (Kawai et al., 2016b)	Tsunami Earthquake	Training	Rift HMD (VST) Tablet-based (VST)	Yes	High Schools	Movement
6	(Iguchi et al., 2016)	Earthquake	Training	Cardboard smartphone (VST)	Yes	Preschools	Pre-evacuation and Movement
7	(Kawai et al., 2016a) (Mitsuhara et al., 2016)	Tsunami	Training	Moverio - smart glasses (OST)	No	University	Movement
8	(Mitsuhara, Iguchi, et al., 2017)	Earthquake	Training	Rift HMD (VST) Cardboard smartphone (VST) Moverio - smart glasses (OST)	Yes only for Cardboard and Moverio	Preschools	Pre-evacuation and Movement
9	(Ortakci et al., 2017)	Fire	Indoor navigation	Smartphone (VST)	No	Large scale buildings	Movement
10	(Mitsuhara, Iwaka, et al., 2017)	Tsunami Earthquake	Training	Tablet (VST)	GPS	Outdoor	Movement
11	(Stigall & Sharma, 2017)	Fire	Training/ Indoor navigation	Tablet (VST)	Yes	University	Movement
12	(Ian Lochhead & Hedley, 2018)	General	Simulation Visualisation	Smartphone and Tablet (VST)	Yes	General	Movement
13	(Diao & Shih, 2018)	General	Indoor navigation	Smartphone (VST)	No	University	Movement
14	(Cai et al., 2018)	General	Indoor navigation	HoloLens (OST)	No	University	Movement
15	(I. Lochhead & Hedley, 2018)	General	Indoor navigation	Smartphone (VST)	Yes	University	Movement
16	(Saunders et al., 2018) (Sharma et al., 2019)	Fire	Training	Microsoft HoloLens (OST) Smartphone and Tablet (VST)	Yes	University	Movement
17	(Mitsuhara et al., 2019)	General	Outdoor navigation	Tablet (VST)	No	Outdoor	Movement
18	(Kitamura et al., 2019)	General	Indoor navigation	Digital mirror AR signage (VST)	NA	NA	Movement
19	(Catal et al., 2019)	Fire	Indoor navigation	Smartphone (VST)	Yes	University	Movement

*VST: video-see-through, OST: optical-see-through

3.3 Evacuation Stages

Next, we review the potential use of AR solutions across the individual stages of the evacuation process (Figure 4). Most reviewed applications focus on the movement stage during building evacuations. In fact, all the AR solutions in Table 1 provide wayfinding information to building occupants to enhance their evacuation performance. The training applications used AR contents to enhance the realism of the evacuation routes with visual cues (e.g. by simulating fire and smoke) or the impact of the disasters on the building and its occupants (e.g. by visualizing cracks and injured occupants). Only two applications focus on the pre-evacuation stage: Mitsuhara, Iguchi and Shishibori (2017), Iguchi, Mitsuhara and Shishibori (2016) developed a training AR application for school teachers. The participants were asked to interact with digital preschool students during an earthquake before starting evacuating until the end of the shake.

3.4 Validation Studies

A final aspect investigated in this review is the comparison between AR solutions and traditional solutions for training and navigation purposes (see Section 3.1). This review has identified only two studies validating the efficacy of AR solutions for navigation purposes comparing them with traditional approaches. Ortakci *et al*, (2017) compared an AR application to a traditional evacuation system (i.e., traditional exit signs). The study suggested that AR solutions could generate safer evacuation procedures. However, the study only reports on data from three participants and more data will need to be collected. Some studies have tested AR wayfinding applications in fields related to evacuation. Diao and Shih (2018), for example, compared the performance of participants who either used an AR navigation tools or a traditional map to escape from a maze in dark conditions. The experiment highlighted that AR navigation can reduce pathfinding time and travelled distance. However, future work will have to test this or similar applications in more realistic environments. AR can also be used to assist navigation for users with impaired vision. Multiple AR navigational aids have been tested with visually impaired users or participants with simulated impaired vision (Huang et al., 2019; Max Kinateder, Gualtieri, et al., 2018; Legge et al., 2013; Tian, Yang, Yi, & Arditi, 2013; Zhao, Kupferstein, Castro, Feiner, & Azenkot, 2019). Conceivably, challenges for evacuation under low visibility conditions (e.g., due to smoke) could provide similar solutions. No direct evidence has been yet provided on the efficacy of AR training solutions when compared with traditional drills, video or presentation-based training. However, similar studies based on VR technology have shown that new technologies and gamification can have better training performance compared to traditional approaches (Ruggiero Lovreglio et al., 2020).

4. SWOT Analysis

Here, we provide a qualitative discussion of AR for *research* on human behaviour and as a *training* tool using a SWOT analysis approach. The acronym SWOT stands for Strengths, Weaknesses, Opportunities, and Threats of a given method or product (Rizzo & Kim, 2005). Strengths refer to inherent resources and capacities of AR. Weaknesses refer to the inherent shortcomings, limitations, and problems of a method. Opportunities describe the ecosystem of conditions that may afford to overcome weaknesses. Finally, threats are those surrounding conditions which hinder the acceptance of a method.

As previously mentioned, AR can be used for research and training purposes (S. M. V. Gwynne et al., 2017). Although there is significant overlap between those two areas, different assessment criteria need to be applied to training and research respectively. For research, the key questions relate to the objectivity, reliability, and validity of a method, as well as verification and validation (Adams, 2011; Cronbach & Meehl, 1955; M. Kinateder & Ronchi, 2019; Pelargos et al., 2017; Ronchi, Kuligowski, Nilsson, Peacock, & Reneke, 2014). For training, the crucial question is whether or not the behaviour learned in training does translate into real-world behaviour (Duperrex, Bunn, & Roberts, 2002). For the purpose of this review, we mostly focus on the research aspects although many of the criteria apply to both purposes.

Table 2 Overview of SWOT analysis

Strengths	Weaknesses	Opportunities	Threats
• Internal validity • Replicability • Safety of participants • Real-time feedback • Precise measurement • Low costs compared to other methods • Design flexibility • Independent of imagination abilities/willingness of participants • No simulator sickness compared to VR • Navigation in real-world environment • Reduced need for 3D models • Ease of transportation and setup (as of 2019)	• Need for confirmation/validation • Inter-individual differences in ease of interaction with AR • Technical limitations • No gold standard available yet; technology not mature • Costs for development and maintenance of AR software • Limited computational power of AR hardware	• Intuitive and natural user interfaces • Graphical developments • Multi-modal simulation and feedback • Usability for researchers • Exchange of 3D-scenes or experiments • Integration in BIM-based design and evacuation modelling • Proliferation of AR ready consumer devices • Access to cloud computing	• Failure to show validity • Failure to show training success in real world. • Misleading expectations • Technical obstacles • Privacy

4.1 Strengths

- Internal validity. High levels of experimental control over AR content allow rigorous experimental manipulation and causal analysis. AR offers less experimental control compared to VR as there is less possibility to control the environment in which the holograms are projected. In VR it is possible to completely control the events that a user sees. However, AR still gives developers higher control over laboratory and field experiments as the holograms (which can represent other evacuee or building features like exit signs) can be easily controlled by the developers.
- Replicability. The content and data created for AR studies can be easily shared. In theory, any user with the right hard and software can, therefore, recreate thus replicate AR experiments. Study setups and AR applications can be shared by researchers, for instance, on platforms such as the Open Science Framework (Nosek et al., 2015).
- Design flexibility. AR studies can simulate a wide range of scenarios in safe laboratory environments. Experimental procedures and content can be easily adjusted in AR, allowing for rapid piloting and fast development of alterations in the experimental set-up. For instance, a researcher could develop a series of design options for a novel type of evacuation signage and project CAD designs into the real world using an AR device. Any changes to the design can then be implemented before an actual physical prototype is built.
- AR applications can provide real-time feedback for users (e.g., on task performance).
- Behaviour (e.g., wayfinding) can be measured at a relatively high level of precision in AR (in terms of temporal and spatial resolution). For instance, current AR devices allow tracking of user position, orientation and input at around 60Hz. The spatial resolution of these measurements is typically within the sub cm range.
- Low costs compared to other methods: The proliferation of affordable consumer AR hardware (e.g., smartphones and Head-Mounted Displays), made AR widely accessible for researchers and practitioners. In comparison to specialized custom hardware, the increasing range of commercial AR products benefits from the cost-savings of mass production, enhanced form factors, and options to support a range of software applications (“apps”).
- Independent of imagination abilities/willingness of participants: Traditional survey and interview

methods require participants to either remember or to imagine certain scenarios (e.g., "imagine that you hear a fire alarm"). In AR – and VR for that matter – participants can be presented with a plethora of scenarios and design options, independent of their ability/willingness to imagine the scenario in question. Further, the researcher has full control over the visual appearance of the scenario, which reduces the number of resources required to carefully describe scenarios to participants.

- Simulator sickness is less prevalent in AR compared to VR simulations (Vovk, Wild, Guest, & Kuula, 2018).
- Navigation in a real-world environment: AR applications allow users to navigate naturally in a real-world environment. This is another particular strength of AR compared to VR. In VR, users are typically tethered to a cable, limiting the range a user can physically walk. As a workaround, VR applications typically require users to navigate with the help of input devices such as gamepads.
- Reduced need for 3D models: Compared to VR, AR typically requires fewer 3D models. For instance, VR requires the researcher to create the full 3D environment that he/she wants the user to experience. While this provides full control over the visual user experience, content creation in VR is associated with the significant workload. In AR, the researcher "only" need to create the 3D objects that they are specifically interested in and not the entire environment. For example, if a researcher wanted to test an evacuation signage system in VR, testing most likely would require the creation of a complete virtual building; in AR it might be sufficient to create the signage system and project it onto an existing physical space.
- Ease of transportation and setup: AR hardware typically consists of standalone systems (either in the form of an HMD or a smartphone). Thus, AR hardware is extremely mobile and can be easily transported to almost any location. In turn, many VR systems require hardware in addition to the HMD (e.g., computer and tracking devices). Thus VR hardware, as of 2019, requires more efforts to transport and setup compared to AR.

4.2 Weaknesses

- Need for confirmation/validation: To date, there are still no empirical studies testing the validity of AR for evacuation research purposes. Previous work in AR is promising, but future validation studies are still necessary. The case is different for AR for training purposes, however. Several studies have shown that AR training can help to improve the realism of the training, as highlighted in Section 3.1. However, domain-specific motivation appears to be correlated with the effectiveness of AR training devices (Georgiou & Kyza, 2018).
- Inter-individual differences in ease of interaction with AR: As with any emerging technology, general questions of usability and human factors need to be considered (Jerónimo, de Antonio, & Moral, 2018; Khalis & Mikami, 2018). Factors, such as sex, age or experience with AR, can influence how easily users may interact with AR technology (Ahmad, Goldiez, & Hancock, 2012)
- Technical limitations: AR technology is maturing rapidly. However, several current (2019) technical limitations need to be taken into account. For instance, the display size in AR systems is currently relatively small compared to VR applications. Besides, additive light displays are limited in the range of colour they can display and the level of brightness especially when referring to *optical-see-through* devices (Kun, Meulen, & Janssen, 2017). In addition, AR systems need to build and update representations of the physical environment. For this, the systems either have to rely on external or built-in sensors. Both approaches have their limitations. For instance, internal sensors are still limited in their refresh rate and range. Consequently, they typically work best in relatively small and static indoor environments.
- Currently, no gold standards exist regarding hardware, software, or human-computer interaction in AR. This is indicative of the immature state of the technology. However, this is likely to change with the release of new generations of AR *optical-see-through* devices, such as HoloLens 2 (Microsoft, 2019).
- Costs for development and maintenance of AR software. One of the major challenges for AR as a research tool is the costs associated with the development and maintenance of AR software. Creating plausible virtual scenarios is complex and requires expertise with specialised hardware and software. Given the rapid developments in this type of technology, a constant investment may be required to stay up-to-date.
- Limited computational power. The mobile nature of most AR devices limits the access to computational power, memory and storage. This limit, among others, the rate at which spatial representations can be refreshed, the weight of computational processes, and the size of files that can be handled. However, the increasing availability of broadband internet via cellular or wireless local area networks, promises to overcome many of these limitations.

4.3 Opportunities

- Intuitive and natural user interfaces. Current AR systems typically offer user interaction either via voice commands, hand gestures, or via input devices (e.g., gamepads). Each of these options comes with its own unique challenges and opportunities. For instance, intuitive interaction via hand gestures that are captured and interpreted by an AR system is a relatively new design challenge. Gestures need to be easy and intuitive to perform, while at the same time precise enough so that the system can interpret the user input appropriately (Kyriazakos, Nikolakis, & Moustakas, 2016; Liang, Yuan, Thalmann, & Thalmann, 2015). While hand gestures are inspired by traditional computer input mechanisms (e.g., users typically can perform similar actions compared to a computer mouse), the lack of haptic feedback remains a challenge (Azmandian, Hancock, Benko, Ofek, & Wilson, 2016; Krichenbauer, Yamamoto, Taketom, Sandor, & Kato, 2018).
  Significant progress has also been made in the area of voice input and several systems have been deployed to the mass consumer market. Voice input promises complete hands-free navigation and interaction with the device. However, this technology is (currently) not as flexible as other input technologies, and users may only have access to limited sets of specific voice commands (Chen, Li, Hua, Shen, & Basu, 2017).
  Input devices, such as clickers and gamepads, can be paired with AR systems. They allow for a wider and more flexible range of input opportunities but may become obsolete with improved device/hands-free input opportunities. For instances, improved tracking capabilities (e.g., of hand and eye movement) may one day lead to fully immersive interactivity (Bohn, 2013; Kim et al., 2017).
- Graphical developments. Current head-mounted see-through AR displays are limited in the size of their field of view and are significantly smaller compared to VR displays. For instance, current VR displays typically have a field of view of around 110º (the human binocular horizontal field of view spans 114 º), whereas HoloLens2 has a 43°×29° field of view (UPLOAD, 2019). In addition, the range of colour space available (e.g., additive light displays cannot display "black"), and the display resolution. However, second-generation AR displays already promise massive improvements in this area.
- Multi-modal simulation and feedback. The integration of multi-modal content that goes beyond visual and auditory simulations remains a challenge. For instance, extended by kinaesthetic, olfactory, haptic, thermoceptive or nociceptive stimulation, although technically conceivable, are currently not at the forefront of commercial technology development. In particular, integration of olfactory and heat simulation seems to be relevant in the context of fire safety research and have to rely on niche product development (Mavrikios, Karabatsou, Fragos, & Chryssolouris, 2006).
- Usability for researchers. Usability of software tools used to build AR content is a challenge in itself. Ease of access and intuitive use of content creation software, as well as the ability to integrate a wide range of data sources, can help to spread the use of AR for research.
- Exchange of 3D-scenes or experiments. A significant amount of time and resources can go into the development of 3D models and scenes. Improved exchange platforms of, for example, 3D models and the proliferation of automated content creation could help to reduce the costs associated with AR tools. Compared to VR, AR should require significantly less content creation, since content only needs to be developed for items interest and not a completely virtual environment.
- Integration of Building Information Modeling (BIM) based design and evacuation modelling. Recent developments in modelling whole buildings (BIM), as well as simulation of complex occupants, flows provide new levels of supplication for building planners and researchers alike (Rüppel & Schatz, 2011). Integration of such technologies into AR systems could be used to visualize fire development and evacuation behaviour within existing or newly planned structures.
- The proliferation of AR ready consumer devices. AR systems have enjoyed great progress thanks to the successful introduction of AR to the mass consumer market. The introduction of large numbers of users promises to boost future development, even for niche applications such as fire safety research at a reduced cost for hardware.
- Access to cloud computing. The recent increase in mobile computational power (e.g., new broadband cellular network technology) will increase the number of computations that can be offloaded to cloud computing services and reduce the computational power needed on devices.

4.4 Threats

- Failure to show validity. This can be considered the biggest threat to AR as a research tool to study pedestrian evacuation. Only if effects in AR are comparable to what might be expected in the real world, it can be considered as useful. However, systematic validation studies of AR has still not tested its range of applicability. Future studies are clearly necessary to test the ecological validity of AR.
- Failure to show training success in the real world. AR training systems can only be considered useful if

the behaviour practised in AR translates into real-world behavioural changes. For instance, an AR wayfinding training that does not improve evacuation wayfinding would have limited use. Future research is needed to test, how well the AR training systems fare compared to other training methods.

- Misleading expectations. AR is an emerging technology and far from reaching maturity. Researchers and developers need to be careful in communicating its SWOTs to not create misleading expectations. AR, just as any other research tool, has its limitations (as discussed here).
- Privacy: Most AR devices collect, analyse, and redistribute huge amounts of use-specific data, which raises concerns over privacy and security. For instance, recording the user environment in real-time or measuring of biometric information, as some devices do, has, depending on the jurisdiction, potential legal and ethical issues that will need to be resolved.
- Technical obstacles. Current AR systems still face many technical obstacles (some of which are discussed above). These need to be overcome before AR can be considered a mature technology and move from niche applications to the mainstream.

The SWOT analysis shows that AR fills some gaps when compared to VR or other methods of data collection and training. As AR is still an emerging technology, very few studies have systematically compared human behaviour in VR, AR and the real world, limiting the level of evidence of the present SWOT analysis. Some work, however, has been done in other fields. One study reporting on affordances (in this case estimated "passability" of an aperture) found that participants responded similarly in AR, VR and real-world laboratory environments (Pointon, Thompson, Creem-Regehr, Stefanucci, & Bodenheimer, 2018). Similarly, a study comparing AR-based exposure therapy (a form of psychotherapy) found comparable effectiveness of treatment in AR, VR, and the real world (Suso-Ribera et al., 2019). Finally, a study asking participants to complete a cooking task in VR and AR, found that participants were able to complete the task slightly faster in AR (Chicchi Giglioli, Bermejo Vidal, & Alcañiz Raya, 2019). Future work is clearly necessary to compare AR as a research tool in human behaviour in disasters. Yet, the rapid development of consumer AR devices gives reason for optimism that the technical challenges that the current devices have (e.g., limited field of view, etc.) will eventually be overcome and that more systematic comparisons of AR and other methods will be published. As bright as the future of AR appears in general, however, the field of pedestrian evacuation will need to address the threats identified here. The most urgent issues, in our view, relate to validation and training effectiveness. AR will only become useful if observations and trained behaviour in AR translate into real-world pedestrian evacuation behaviour.

5. Conclusion

Here, we reviewed the literature on Augmented Reality (AR) applications developed for building evacuations. We identified 23 relevant conference and journal papers and one patent. The relatively small but quickly rising number of publications (Figure 6) shows that AR is still not widely adopted in the field but its potential has been recognized by a range of researchers and users. We also found that applications have been developed mainly for disasters such as tsunamis, earthquakes and fires affecting educational buildings and large-scale buildings. As such, applications for many other man-made or natural disasters (e.g. terrorist attacks, bushfires, or hurricanes) have not been investigated yet.

In most cases, AR applications were used for training purposes and to enhance the realism of traditional evacuation drills by adding virtual content. Moreover, several applications have been developed with the aim of providing building occupants with wayfinding solutions to enhance their evacuation performance. A novel application is the use of AR to visualize the result of evacuation simulation in real-world contexts.

We found that researchers use both indirect (VSF) and direct AR technologies (OSF). The review indicates that indirect immersive AR solutions such as Rift can generate motion sickness while direct AR solutions have a limited field of view that reduces the immersion. Those existing hardware limitations will likely be overcome in the near future. However, to date (October 2019), implementations using those two innovative solutions are still not available.

This review illustrates that all the AR applications were developed to affect the movement stage during building evacuations and only in two instances those applications were used for training purpose during the pre-evacuation stage. Therefore, future studies are necessary to investigate how AR tools can enhance pre-evacuation training and how those tools can support building occupants during real emergencies, e.g., by providing them with information on the optimal actions to take.

AR is still an emerging technology, as illustrated by the publication dates shown in Figure 6. Despite the current weaknesses and threats, the promises of the technology allow for some speculation about potential future applications. These applications will, of course, be on the research side, but an even larger impact is expected to emerge from applications helping people to respond to disasters. Some ideas for such applications have been presented here (see Table 1). Future applications may, for example, guide occupants towards safe egress routes, taking real-time information into account. This could improve the evacuation outcomes on an individual level but also on an aggregated (i.e. building) level, by using the position of individual occupants to distribute all occupants efficiently onto different egress routes. This data could be integrated with the information provided by buildings (e.g. elevators, sprinkler systems) or transportation systems (e.g. road closures, traffic). With future applications come new requirements for AR systems. What does the ideal AR system for this application look like? What are the requirements in terms of field-of-view, tracking, interaction/communication between devices, and so on? Would we expect a difference in outcomes for the form of video-see-through AR supported on current smartphones versus optical-see-through AR headsets? All of these questions are still open today and will have to be addressed in future research. The SWOT analysis highlighted that AR already fills some gaps when compared to VR and other methods. At the same time, the analysis also revealed that there are still many open questions and limitations.

References

Adams, H. F. (2011). Validity, reliability, and objectivity. *Psychological Monographs*, *47*(2), 329–350. https://doi.org/10.1037/h0093421

Ahmad, A. M., Goldiez, B. F., & Hancock, P. A. (2012). Gender Differences in Navigation and Wayfinding using Mobile Augmented Reality. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *49*(21), 1868–1872. https://doi.org/10.1177/154193120504902111

Ahn, J., & Han, R. (2011). RescueMe: An Indoor Mobile Augmented-Reality Evacuation System by Personalized Pedometry. *2011 IEEE Asia-Pacific Services Computing Conference*, 70–77. https://doi.org/10.1109/APSCC.2011.26

Ahn, J., & Han, R. (2012). An indoor augmented-reality evacuation system for the Smartphone using personalized Pedometry. *Human-Centric Computing and Information Sciences*, *2*(1), 18. https://doi.org/10.1186/2192-1962-2-18

Amos, M., Bénichou, N., Gwynne, S., & Kinateder, M. (2019). *NEED Project: Evacuation Drill Roadmap Document - National Research Council Canada Report*.

Asgary, A. (2017). *Holodisaster: Leveraging Microsoft HoloLens in Disaster and Emergency Management. IAEM Bulletin*.

Azmandian, M., Hancock, M., Benko, H., Ofek, E., & Wilson, A. D. (2016). Haptic Retargeting: Dynamic Repurposing of Passive Haptics for Enhanced Virtual Reality Experiences. *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems - CHI '16*, 1968–1979. https://doi.org/10.1145/2858036.2858226

Bernardini, G., D'Orazio, M., & Quagliarini, E. (2016). Towards a "behavioural design" approach for seismic risk reduction strategies of buildings and their environment. *Safety Science*, *86*, 273–294. https://doi.org/10.1016/j.ssci.2016.03.010

Bernardini, G., Lovreglio, R., & Quagliarini, E. (2019). Proposing behavior-oriented strategies for earthquake emergency evacuation: A behavioral data analysis from New Zealand, Italy and Japan. *Safety Science*, *116*, 295–309. https://doi.org/10.1016/J.SSCI.2019.03.023

Bohn, D. D. (2013). *U.S. Patent No. 8,998,414. Washington, DC: U.S. Integrated eye tracking and display system*.

Cai, L., Yang, R., & Tao, Z. (2018). A new method of evaluating signage system using mixed reality and eye tracking. *4th ACM SIGSPATIAL International Workshop on Safety and Resilience*.

Carmigniani, J., Furht, B., Anisetti, M., Ceravolo, P., Damiani, E., & Ivkovic, M. (2011). Augmented reality technologies, systems and applications. *Multimedia Tools and Applications*, *51*(1), 341–377. https://doi.org/10.1007/s11042-010-0660-6

Catal, C., Akbulut, A., Tunali, B., Ulug, E., & Ozturk, E. (2019). Evaluation of augmented reality technology for the design of an evacuation training game. *Virtual Reality*, 1–10. https://doi.org/10.1007/s10055-019-00410-z

Chen, Z., Li, J., Hua, Y., Shen, R., & Basu, A. (2017). Multimodal interaction in augmented reality. *2017 IEEE International Conference on Systems, Man, and Cybernetics (SMC)*, 206–209. https://doi.org/10.1109/SMC.2017.8122603

Chicchi Giglioli, I. A., Bermejo Vidal, C., & Alcañiz Raya, M. (2019). A Virtual Versus an Augmented Reality Cooking Task Based-Tools: A Behavioral and Physiological Study on the Assessment of Executive Functions. *Frontiers in Psychology*, *10*. https://doi.org/10.3389/fpsyg.2019.02529

Cronbach, L. J., & Meehl, P. E. (1955). Construct validity in psychological tests. *Psychological Bulletin*, *52*(4), 281–302. https://doi.org/10.1037/h0040957

Diao, P. H., & Shih, N. J. (2018). MARINS: A mobile smartphone AR system for pathfinding in a dark environment. *Sensors (Switzerland)*. https://doi.org/10.3390/s18103442

Duperrex, O., Bunn, F., & Roberts, I. (2002). Safety education of pedestrians for injury prevention: a systematic review of randomised controlled trials. *BMJ (Clinical Research Ed.)*, *324*(7346), 1129. https://doi.org/10.1136/bmj.324.7346.1129

Feng, Y., Duives, D. C., Daamen, W., & Hoogendoorn, S. P. (2019). *Pedestrian exit choice behavior during an evacuation - a comparison study between field and VR experiment*. Retrieved from https://www.narcis.nl/publication/RecordID/oai:tudelft.nl:uuid%3A5238572e-9923-44b8-9b7a-e294a7e473c8

Feng, Z., González, V. A., Amor, R., Lovreglio, R., & Cabrera-Guerrero, G. (2018). Immersive virtual reality serious games for evacuation training and research: A systematic literature review. *Computers & Education*, *127*, 252–266. https://doi.org/10.1016/J.COMPEDU.2018.09.002

Feng Zhou, Duh, H. B.-L., & Billinghurst, M. (2008). Trends in augmented reality tracking, interaction and display: A review of ten years of ISMAR. *2008 7th IEEE/ACM International Symposium on Mixed and Augmented Reality*, 193–202. https://doi.org/10.1109/ISMAR.2008.4637362

Georgiou, Y., & Kyza, E. A. (2018). Relations between student motivation, immersion and learning outcomes in location-based augmented reality settings. *Computers in Human Behavior*, *89*, 173–181. https://doi.org/10.1016/j.chb.2018.08.011

Gwynne, S. M. V., Boyce, K. E., Kuligowski, E. D., Nilsson, D., Robbins, A., & Lovreglio, R. (2016). Pros and Cons of Egress Drills. *Interflam 2016*. London, UK.

Gwynne, S. M. V., Kuligowski, E. D., Boyce, K. E., Nilsson, D., Robbins, A. P., Lovreglio, R., … Roy-Poirier, A. (2017). Enhancing egress drills: Preparation and assessment of evacuee performance. *Fire and Materials*. https://doi.org/10.1002/fam.2448

Gwynne, Steve M., Galea, E. R., Owen, M., Lawrence, P. J., & Filippidis, L. (1999). A review of the methodologies used in evacuation modelling. *Fire and Materials*, *23*(6), 383–388. https://doi.org/10.1002/(SICI)1099-1018(199911/12)23:6<383::AID-FAM715>3.0.CO;2-2

Gwynne, S. M. V., & Boyce, K. E. (2016). Engineering Data. In *SFPE Handbook of Fire Protection Engineering* (pp. 2429–2551). https://doi.org/10.1007/978-1-4939-2565-0_64

Huang, J., Kinateder, M., Dunn, M. J., Jarosz, W., Yang, X.-D., & Cooper, E. A. (2019). An augmented reality sign-reading assistant for users with reduced vision. *PLOS ONE*, *14*(1), e0210630. https://doi.org/10.1371/journal.pone.0210630

Iguchi, K., Mitsuhara, H., & Shishibori, M. (2016). Evacuation instruction training system using augmented reality and a smartphone-based head mounted display. *2016 3rd International Conference on Information and Communication Technologies for Disaster Management (ICT-DM)*, 1–6. https://doi.org/10.1109/ICT-DM.2016.7857220

Jerónimo, J., de Antonio, A., & Moral, C. (2018, September 19). *Architectural challenges on the analysis of human behaviour in synthetic environments*. 1–7. https://doi.org/10.1145/3241403.3241441

Kawai, J., Mitsuhara, H., & Shishibori, M. (2015). Tsunami Evacuation Drill System Using Smart Glasses. *Procedia - Procedia Computer Science*, *72*, 329–336. https://doi.org/10.1016/j.procs.2015.12.147

Kawai, J., Mitsuhara, H., & Shishibori, M. (2016a). Game-based evacuation drill using augmented reality and head-mounted display. *Interactive Technology and Smart Education*, *13*(3), 186–201. https://doi.org/10.1108/ITSE-01-2016-0001

Kawai, J., Mitsuhara, H., & Shishibori, M. (2016b). Tsunami evacuation drill system using motion hazard map and smart devices. *2016 3rd International Conference on Information and Communication Technologies for Disaster Management (ICT-DM)*, 1–7. https://doi.org/10.1109/ICT-DM.2016.7857221

Khalis, A., & Mikami, A. Y. (2018). Who's Gotta Catch 'Em All?: Individual differences in Pokèmon Go gameplay behaviors. *Personality and Individual Differences*, *124*, 35–38. https://doi.org/10.1016/j.paid.2017.11.049

Kim, J., Kwak, Y. H., Kim, W., Park, K., Pak, J. J., & Kim, K. (2017). Flexible force sensor based input device for gesture recognition applicable to augmented and virtual realities. *2017 14th International Conference on Ubiquitous Robots and Ambient Intelligence (URAI)*, 271–273. https://doi.org/10.1109/URAI.2017.7992727

Kinateder, M., & Ronchi, E. (2019). Letter to the Editor: Burning Down the Silos in a Multidisciplinary Field. Towards Unified Quality Criteria in Human Behaviour in Fire. *Fire Technology*. https://doi.org/10.1007/s10694-019-00867-z

Kinateder, Max, Gualtieri, J., Dunn, M. J., Jarosz, W., Yang, X.-D., & Cooper, E. A. (2018). Using an Augmented Reality Device as a Distance-based Vision Aid—Promise and Limitations. *Optometry and Vision Science*, *95*(9), 727–737. https://doi.org/10.1097/OPX.0000000000001232

Kinateder, Max, Ronchi, E., Nilsson, D., Kobes, M., Müller, M., Pauli, P., & Mühlberger, A. (2014). Virtual Reality for Fire Evacuation Research. *Computer Science and Information Systems (FedCSIS)*, 313–321.

https://doi.org/10.15439/2014F94
Kinateder, Max, Wirth, T. D., & Warren, W. H. (2018). *Crowd Dynamics in Virtual Reality*. https://doi.org/10.1007/978-3-030-05129-7_2
Kitamura, T., Yasui, K., & Nakatani, Y. (2019). *Proposal of Using Digital Mirror Signage and AR Pictogram for Follow Me Evacuation Guidance*. 307–314. https://doi.org/10.1007/978-3-030-22636-7_22
Krichenbauer, M., Yamamoto, G., Taketom, T., Sandor, C., & Kato, H. (2018). Augmented Reality versus Virtual Reality for 3D Object Manipulation. *IEEE Transactions on Visualization and Computer Graphics*, *24*(2), 1038–1048. https://doi.org/10.1109/TVCG.2017.2658570
Kuligowski, E.D. (2016). Computer Evacuation Models for Buildings. In *SFPE Handbook of Fire Protection Engineering* (pp. 2152–2180).
Kuligowski, Erica D., Peacock, R. D., & Hoskins, B. L. (2010). *A Review of Building Evacuation Models, 2nd Edition-Technical Note (NIST TN) - 1680*. Gaithersburg.
Kuligowski, Erica D. (2016). Human behavior in fire. In *SFPE Handbook of Fire Protection Engineering* (pp. 2070–2114). Springer.
Kun, A. L., Meulen, H. van der, & Janssen, C. P. (2017). Calling While Driving: An Initial Experiment with HoloLens. *Proceedings of the 9th International Driving Symposium on Human Factors in Driver Assessment, Training, and Vehicle Design: Driving Assessment 2017*, 200–206. https://doi.org/10.17077/drivingassessment.1636
Kyriazakos, V., Nikolakis, G., & Moustakas, K. (2016). *Natural Interaction with 3D Content on Mobile AR Systems Using Gesture Recognition*. https://doi.org/10.1007/978-3-319-40651-0_28
Le, Q. T., Pedro, A., Lim, C. R., Park, H. T., Park, C., & Kim, H. K. (2015). *A framework for using mobile based virtual reality and augmented reality for experiential construction safety education*.
Legge, G. E., Beckmann, P. J., Tjan, B. S., Havey, G., Kramer, K., Rolkosky, D., … Rangarajan, A. (2013). Indoor Navigation by People with Visual Impairment Using a Digital Sign System. *PLoS ONE*, *8*(10), e76783. https://doi.org/10.1371/journal.pone.0076783
Li, H., Zhang, J., Xia, L., Song, W., & Bode, N. W. F. (2019). Comparing the route-choice behavior of pedestrians around obstacles in a virtual experiment and a field study. *Transportation Research Part C: Emerging Technologies*, *107*, 120–136. https://doi.org/10.1016/J.TRC.2019.08.012
Li, X., Yi, W., Chi, H.-L., Wang, X., & Chan, A. P. C. (2018). A critical review of virtual and augmented reality (VR/AR) applications in construction safety. *Automation in Construction*, *86*, 150–162. https://doi.org/10.1016/J.AUTCON.2017.11.003
Liang, H., Yuan, J., Thalmann, D., & Thalmann, N. M. (2015). AR in Hand: Egocentric Palm Pose Tracking and Gesture Recognition for Augmented Reality Applications. *Proceedings of the 23rd ACM International Conference on Multimedia - MM '15*, 743–744. https://doi.org/10.1145/2733373.2807972
Lindell, M. K., & Perry, R. W. (2012). The Protective Action Decision Model: Theoretical Modifications and Additional Evidence. *Risk Analysis*, *32*(4), 616–632. https://doi.org/10.1111/j.1539-6924.2011.01647.x
Lochhead, I., & Hedley, N. (2018). Communicating multilevel evacuation context using situated augmented reality. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *4*(4/W6), 33–40. https://doi.org/10.5194/isprs-annals-IV-4-W6-33-2018
Lochhead, Ian, & Hedley, N. (2018). Mixed reality emergency management: bringing virtual evacuation simulations into real-world built environments. *International Journal of Digital Earth*, 1–19. https://doi.org/10.1080/17538947.2018.1425489
López, E., Plá, J., Méndez, G., & Gervás, P. (2010). Augmented Reality and Indoors Wi-Fi Positioning for Conducting Fire Evacuation Drills Using Mobile Phones. *4th International Symposium of Ubiquitous Computing and Ambient Intelligence (UCAmI 2010)*. Retrieved from http://nil.fdi.ucm.es/?q=node/562
Lovreglio, R., Gonzalez, V., Amor, R., Spearpoint, M., Thomas, J., Trotter, M., & Sacks, R. (2017). Enhancing earthquake evacuee safety by using virtual reality serious games. *Lean & Computing in Construction Congress (LC3) 2017*.
Lovreglio, R., Kuligowski, E., Gwynne, S., & Boyce, K. (2019). A pre-evacuation database for use in egress simulations. *Fire Safety Journal*, *105*, 107–128. https://doi.org/10.1016/J.FIRESAF.2018.12.009
Lovreglio, Ruggiero. (2016). *Modelling Decision-Making in Fire Evacuation based on the Random Utility Theory*. Politecnico of Bari, Milan and Turin.
Lovreglio, Ruggiero, Duan, X., Rahout, A., Phipps, R., & Nilsson, D. (2020). Comparing the Effectiveness of Virtual Reality Training and Video Training. *Under Review*.
Lovreglio, Ruggiero, Kuligowski, E. D., Gwynne, S. M. V., & Strahan, K. (2019). A Modelling Framework for Householder Decision-Making for Wildfire Emergencies. *International Journal of Disaster Risk Reduction*.
Lovreglio, Ruggiero, Ronchi, E., & Nilsson, D. (2015). A model of the decision-making process during pre-evacuation. *Fire Safety Tecnology*. https://doi.org/http://dx.doi.org/10.1016/j.firesaf.2015.07.001
Lovreglio, Ruggiero, Ronchi, E., & Nilsson, D. (2016). An Evacuation Decision Model based on perceived risk, social influence and behavioural uncertainty. *Simulation Modelling Practice and Theory*, *66*(April), 226–

242. https://doi.org/10.1016/j.simpat.2016.03.006

Mavrikios, D., Karabatsou, V., Fragos, D., & Chryssolouris, G. (2006). A prototype virtual reality-based demonstrator for immersive and interactive simulation of welding processes. *International Journal of Computer Integrated Manufacturing*, *19*(3), 294–300. https://doi.org/10.1080/09511920500340916

Microsoft. (2016). Japan Airlines creates yet another first-class experience, this time using Microsoft HoloLens.

Microsoft. (2019). HoloLens 2 Mixed reality is ready for business. Retrieved from https://www.microsoft.com/en-us/hololens

Milgram, P., & Kishino, F. (1994). A taxonomy of mixed reality visual displays. *EICE Transactions on Information Systems*.

Mitsuhara, H., Iguchi, K., & Shishibori, M. (2017). Using Digital Game, Augmented Reality, and Head Mounted Displays for Immediate-Action Commander Training. *International Journal of Emerging Technologies in Learning*, *12*(2).

Mitsuhara, H., Iwaka, K., Kozuki, Y., Shishibori, M., Inoue, T., Yaniagiichi, K., … Morimoto, M. (2017). Penumbral tourism: Place-based disaster education via real-world disaster simulation. *Proceedings of the 2016 3rd International Conference on Information and Communication Technologies for Disaster Management, ICT-DM 2016*. https://doi.org/10.1109/ICT-DM.2016.7857222

Mitsuhara, H., Shishibori, M., Kawai, J., & Iguchi, K. (2016). Game-Based Evacuation Drills Using Simple Augmented Reality. *2016 IEEE 16th International Conference on Advanced Learning Technologies (ICALT)*, 133–137. https://doi.org/10.1109/ICALT.2016.71

Mitsuhara, H., Tanimura, C., Nemoto, J., & Shishibori, M. (2019). Why Don't You Evacuate Speedily? Augmented Reality-based Evacuee Visualisation in ICT-based Evacuation Drill. *Proceedings of 2018 IEEE International Conference on Teaching, Assessment, and Learning for Engineering, TALE 2018*. https://doi.org/10.1109/TALE.2018.8615405

Nilsson, D. (2009). *Exit choice in fire emergencies - Influencing choice of exit with flashing lights*. Lund University.

Nilsson, D., & Kinateder, M. (2015). Virtual Rality Experiments - The Future or a Dead End? In K. Boyce (Ed.), *6th international symposium Human Behaviour in Fire* (pp. 13–22). Cambridge: Interscience Communications.

Nosek, B. A., Alter, G., Banks, G. C., Borsboom, D., Bowman, S. D., Breckler, S. J., … Yarkoni, T. (2015, June 26). Promoting an open research culture. *Science*, Vol. 348, pp. 1422–1425. https://doi.org/10.1126/science.aab2374

Ortakci, Y., Atila, U., Demiral, E., Ozacar, K., & Karas, I. R. (2017). Comparison of a Smart Mobile Application-Supported Evacuation System and Traditional Evacuation Systems. *1st IAG Workshop on BIM and GIS Integration*.

Pelargos, P. E., Nagasawa, D. T., Lagman, C., Tenn, S., Demos, J. V., Lee, S. J., … Yang, I. (2017, January 1). Utilizing virtual and augmented reality for educational and clinical enhancements in neurosurgery. *Journal of Clinical Neuroscience*, Vol. 35, pp. 1–4. https://doi.org/10.1016/j.jocn.2016.09.002

Pointon, G., Thompson, C., Creem-Regehr, S., Stefanucci, J., & Bodenheimer, B. (2018). *Affordances as a Measure of Perceptual Fidelity in Augmented Reality*. Retrieved from https://developer.microsoft.com/en-us/windows/mixed-reality

Potts, J., Sookdeo, T., Westerheide, J., & Sharber, D. (2019). Enhanced Augmented/Mixed Reality and Process Safety Applications. *SPE Middle East Oil and Gas Show and Conference*. https://doi.org/10.2118/195059-MS

Rizzo, A. "Skip," & Kim, G. J. (2005). A SWOT Analysis of the Field of Virtual Reality Rehabilitation and Therapy. *Presence: Teleoperators and Virtual Environments*, *14*(2), 119–146. https://doi.org/10.1162/1054746053967094

Ronchi, E., Kuligowski, E. D., Nilsson, D., Peacock, R. D., & Reneke, P. A. (2014). Assessing the Verification and Validation of Building Fire Evacuation Models. *Fire Technology*, 1–23. https://doi.org/10.1007/s10694-014-0432-3

Rüppel, U., & Schatz, K. (2011). Designing a BIM-based serious game for fire safety evacuation simulations. *Advanced Engineering Informatics*, *25*(4), 600–611. https://doi.org/10.1016/j.aei.2011.08.001

Saunders, J., Bodempudi, S. T., Sharma, S., Scribner, D., Grynovicki, J., & Grazaitis, P. (2018). Building Evacuation using Microsoft HoloLens. *SEDE 2018*. New Orleans, LA.

Sharma, S., Bodempudi, S. T., Scribner, D., Grynovicki, J., & Grazaitis, P. (2019). Emergency Response Using HoloLens for Building Evacuation. In *Virtual, Augmented and Mixed Reality. Multimodal Interaction* (pp. 299–311). https://doi.org/10.1007/978-3-030-21607-8_23

Stigall, J. S., & Sharma, S. (2017). Mobile Augmented Reality Application for Building Evacuation Using Intelligent Signs. *ISCA 26th International Conference on Software Engineering and Data Engineering (SEDE-2017)*. San Diego, CA.

Suso-Ribera, C., Fernández-Álvarez, J., García-Palacios, A., Hoffman, H. G., Bretón-López, J., Baños, R. M., …

Botella, C. (2019). Virtual Reality, Augmented Reality, and *In Vivo* Exposure Therapy: A Preliminary Comparison of Treatment Efficacy in Small Animal Phobia. *Cyberpsychology, Behavior, and Social Networking*, *22*(1), 31–38. https://doi.org/10.1089/cyber.2017.0672
Tian, Y., Yang, X., Yi, C., & Arditi, A. (2013). Toward a computer vision-based wayfinding aid for blind persons to access unfamiliar indoor environments. *Machine Vision and Applications*, *24*(3), 521–535. https://doi.org/10.1007/s00138-012-0431-7
Tsai, M. K., Lee, Y. C., Lu, C. H., Chen, M. H., Chou, T. Y., & Yau, N. J. (2012). Integrating geographical information and augmented reality techniques for mobile escape guidelines on nuclear accident sites. *Journal of Environmental Radioactivity*, *109*, 36–44. https://doi.org/10.1016/j.jenvrad.2011.12.025
Tsai, M. K., & Yau, N. J. (2013). Enhancing usability of augmented-reality-based mobile escape guidelines for radioactive accidents. *Journal of Environmental Radioactivity*, *118*, 15–20. https://doi.org/10.1016/j.jenvrad.2012.11.001
UPLOAD. (2019). HoloLens 2's Field of View Revealed.
Vovk, A., Wild, F., Guest, W., & Kuula, T. (2018). Simulator sickness in Augmented Reality training using the Microsoft HoloLens. *Conference on Human Factors in Computing Systems - Proceedings*, *2018-April*, 1–9. https://doi.org/10.1145/3173574.3173783
Wagner, D., & Schmalstieg, D. (2009). History and Future of Tracking for Mobile Phone Augmented Reality. *2009 International Symposium on Ubiquitous Virtual Reality*, 7–10. https://doi.org/10.1109/ISUVR.2009.11
Wang, W., Wu, X., Chen, G., Chen, Z., Wang, W., Wu, X., … Chen, Z. (2018). Holo3DGIS: Leveraging Microsoft HoloLens in 3D Geographic Information. *ISPRS International Journal of Geo-Information*, *7*(2), 60. https://doi.org/10.3390/ijgi7020060
Watts, J. M., & Hall, J. R. (2016). Introduction to Fire Risk Analysis. In *SFPE Handbook of Fire Protection Engineering* (pp. 2817–2826). https://doi.org/10.1007/978-1-4939-2565-0_72
Yi-Wen Cai, & Shih-Cheng Wang. (2011). *Emergency guiding system, server and portable device using augmented reality*. Retrieved from https://patents.google.com/patent/US20130116922
Zhao, Y., Kupferstein, E., Castro, B., Feiner, S., & Azenkot, S. (2019). *Designing AR Visualizations to Facilitate Stair Navigation for People with Low Vision*. https://doi.org/10.1145/3332165.3347906

Augmented reality for pedestrian evacuation research: Promises and limitations

Lovreglio, R

2020-08