



# Augmented reality for pedestrian evacuation research: Promises and limitations

Ruggiero Lovreglio<sup>a</sup>, Max Kinateder<sup>b,\*</sup>

<sup>a</sup> School of Built Environment, Massey University, Auckland, New Zealand

<sup>b</sup> National Research Council Canada, Fire Safety, Ottawa, ON, Canada



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## 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 (2020) relevant literature on AR as a tool to study and improve building evacuation triggered by a variety of disasters such as fires, earthquakes or tsunamis. 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.

## 1. Introduction

Evacuation is a key risk-reduction strategy for buildings threatened by disasters (Bernardini et al., 2016; Watts and 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 et al., 2019; Gwynne et al., 2017; Lovreglio et al., 2019a; 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 (Gwynne et al., 1999; Kuligowski et al., 2010; Lindell and Perry, 2012; 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 (Kinateder et al., 2014; Le et al., 2015; Li et al., 2018). First, VR and AR could provide effective, flexible and affordable training platforms for safety-relevant scenarios. Second, VR and AR as research tools 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 (Feng et al., 2019, 2018; Kinateder et al., 2014, 2018b; Li et al., 2019; Lovreglio et al., 2020; Nilsson and 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 two recent review articles identified potential applications and associated challenges of the method (X. Li et al., 2018; Potts, Sookdeo, Westerheide, and 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 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 without any interaction with the spatial structure of the real world (e.g., by presenting text information in the foreground of a screen), or 3D with consideration of the spatial structure (e.g., by

\* Corresponding author at: National Research Council Canada, Fire Safety, 1200 Montreal Road, Ottawa ON, Canada.

E-mail address: [Max.kinateder@nrc-cnrc.gc.ca](mailto:Max.kinateder@nrc-cnrc.gc.ca) (M. Kinateder).

presenting a virtual object so that it appears to be placed on a real-world object; Carmigniani et al., 2011).<sup>1</sup> As of 2020, 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 and 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 Reality (AR) 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 (Fig. 1).

The technological differences between AR and VR hardware afford different types 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?).

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 Fig. 2a). In video-see-through 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 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 and Han, 2011, 2012; Mitsuahara et al., 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 Fig. 2b). 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 2020, optical-see-through Head-Mounted Displays have still not penetrated the mass consumer market, but several commercial products, such as HoloLens 2 (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 tool for disaster evacuation have been published (Kawai et al., 2016a; Mitsuahara et al., 2017a).

<sup>1</sup> It is worth highlighting that other definitions have been used. For instance, other definitions of *augmented reality* refer to the visualization of only 2D digital contents while *mixed reality* allows an integrated visualization of 3D digital contents and reality.

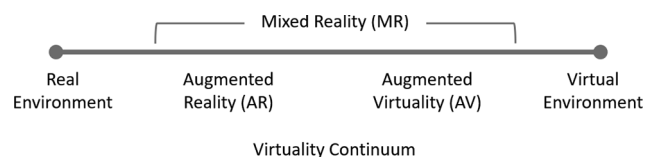


Fig. 1. Virtuality continuum (Milgram and Kishino, 1994).

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 Fig. 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 et al., 2008; Wagner and Schmalstieg, 2009).

### 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 and Boyce, 2016; Kuligowski, 2016a). RSET can be divided into several sequential time periods as shown in Fig. 4. Each step in the timeline needs to be completed for a successful evacuation.

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 (Lovreglio et al., 2019b; Lovreglio et al., 2015, 2016). For other disasters, such as earthquakes, building occupants can easily recognise the threat (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 (Feng et al., 2018; 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.

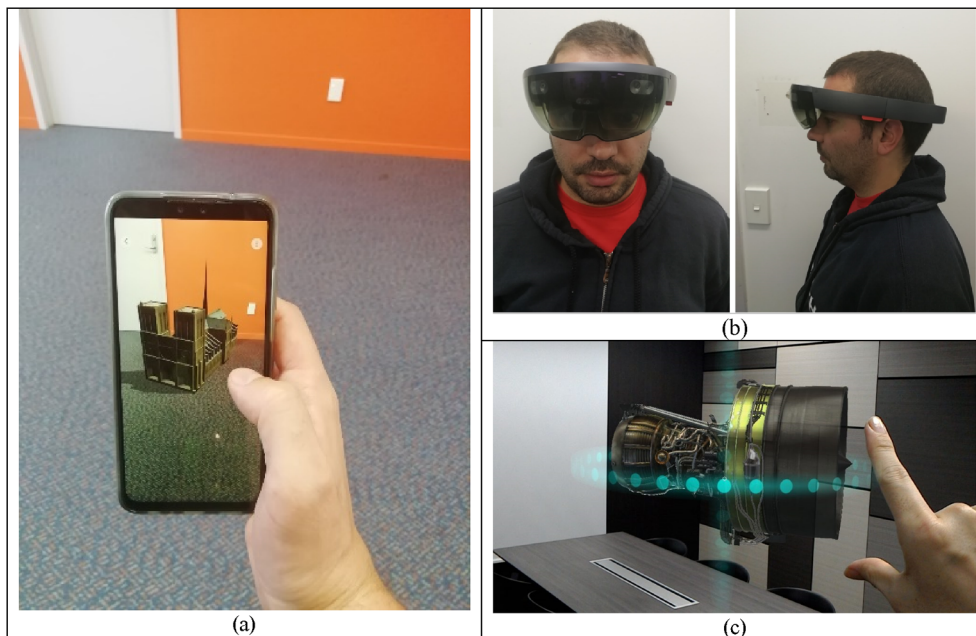


Fig. 2. Example of (a) a video-see-through (VST) device and (b) an optical-see-through (OST) device and (c) its user view (Microsoft, 2016).

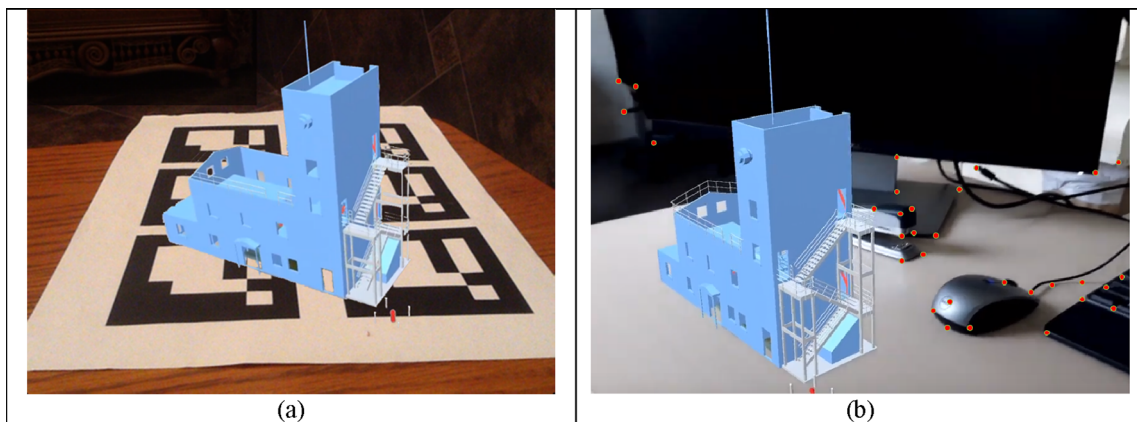


Fig. 3. Example of (a) a marker-based AR application and (b) a markerless AR application (in red the fiducial markers identified in the scene). This figure shows an educational application developed in Unity by the first author. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

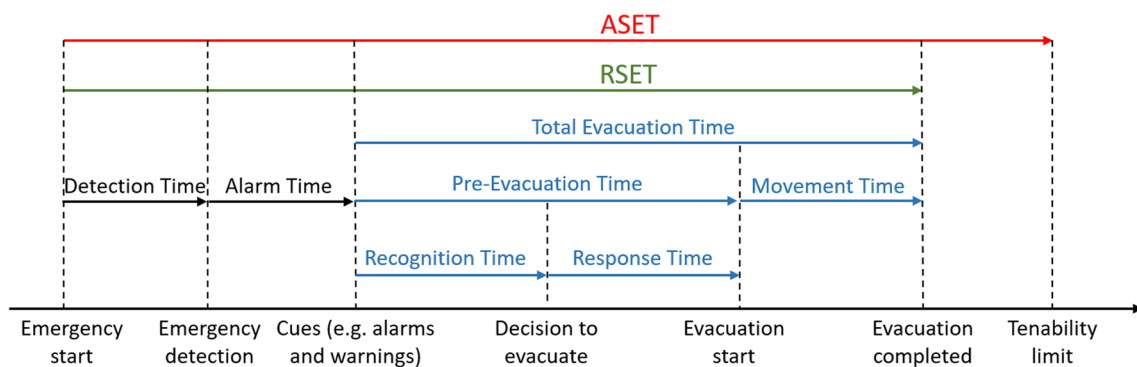


Fig. 4. Timeline building evacuation framework (Kuligowski, 2016b).  
Figure Source: Lovreglio (2016).



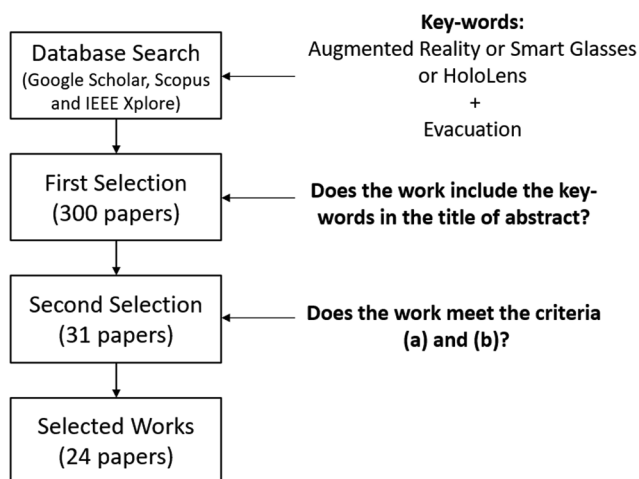


Fig. 5. Selection process for the review.

## 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 initial 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 Fig. 5.

## 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, Fig. 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 (Li et al., 2018).

Table 1 and Fig. 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.

### 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. Mitsuahara et al. (2017a, 2017b), augmented their AR training tool by showing the impact of an earthquake on a building and other people. Iguchi et al. (2016) as well as Mitsuahara et al. (2017a) 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: Mitsuahara et al. (2017a, 2017b) 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 Mitsuahara et al. (2017a) 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 way-finding 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 (Fig. 8). This solution was proposed originally in a patent (Cai and Wang, 2011). Variations of this idea were published for pathfinding in high (Ahn and Han, 2012; Cai et al., 2018) and low visibility conditions (Diao and Shih, 2018). The second type of applications augments the evacuation plan by showing a 3D visualization of the floor where the evacuees are located (Fig. 9). This solution helps the understanding of where a person is and where they need to go to evacuate (Lochhead and Hedley, 2018a; Stigall and 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 Fig. 10. In this case, information is provided by humanoid AR animations indicating the evacuees the direction to take (Kitamura et al., 2019).

The outdoor navigation AR applications proposed by Tsai et al. (2012) and Tsai and Yau (2013) aims at providing real-time augmented information about radioactive threats and the location of the available shelters in case of nuclear accidents. Mitsuahara 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 (2018a, 2018b) 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,

**Table 1**  
Papers selected for review process.

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

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

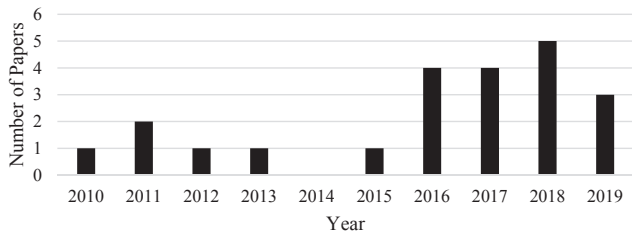


Fig. 6. Number of papers included in the systematic review by year. Note: the data related to 2019 are partial as the review was carried out in August 2019).

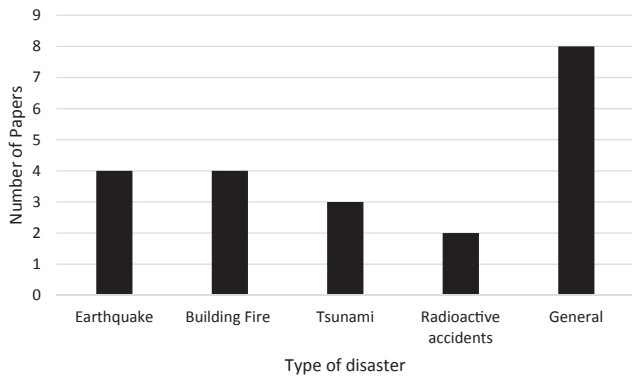


Fig. 7. Number of papers included in the systematic review by type of disasters for the AR applications.

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 et al., 2016b; Mitsuhara et al., 2017a). 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 et al., 2019). At the time of the current review, the first rendition of HoloLens still has several limitations: mapping update rate (ca. 1 Hz); mapping distance; a relatively small field of view (ca. 30° horizontally).

To date, only two studies are comparing the pros and cons of different AR pieces of hardware from a user viewpoint. Mitsuhara et al. (2017a) 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.

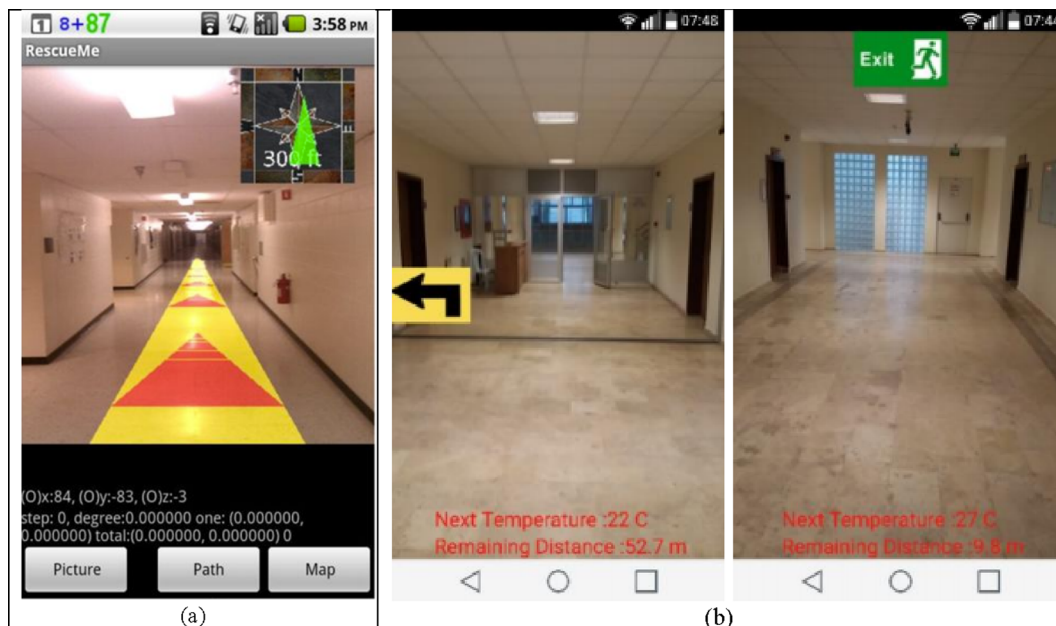


Fig. 8. Examples of AR arrow and exit sign tags: (a) RescueMe (Ahn and Han, 2012) and (b) the smart evacuation system proposed by Ortacki et al. (2017). Figures reproduced with permission.



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

3.3. Evacuation stages

Next, we review the potential use of AR solutions across the individual stages of the evacuation process (Fig. 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: Mitsuhashi et al. (2017a), Iguchi et al. (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; Kinateder et al., 2018a; Legge et al., 2013; Tian et al., 2013; Zhao et al., 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 (Lovreglio et al., 2020).

4. SWOT analysis

Here, we provide a qualitative discussion of AR as a research and training tool using a SWOT analysis approach. The acronym SWOT stands for Strengths, Weaknesses, Opportunities, and Threats of a given method or product (Rizzo and Kim, 2005). Strengths refer to inherent resources and capacities of AR. Weaknesses refer to the inherent

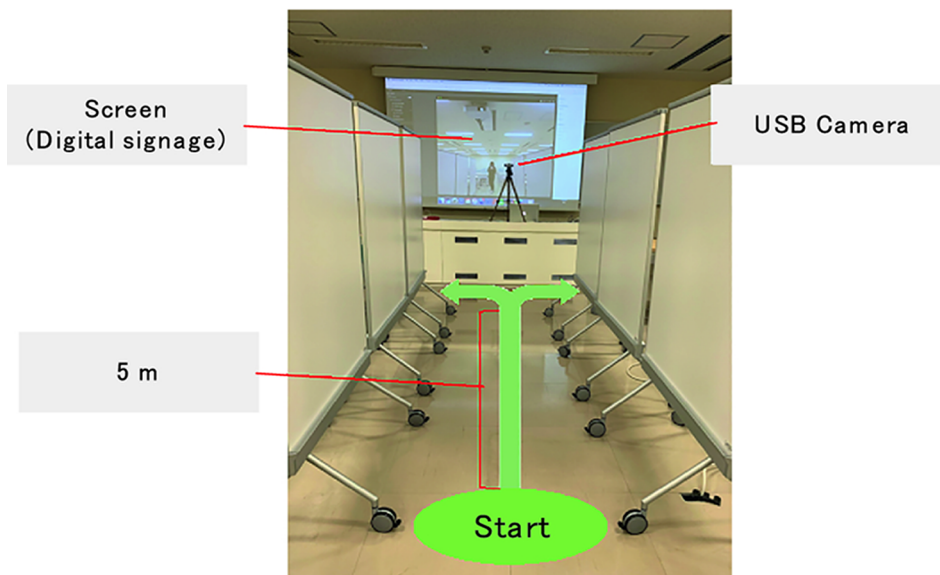


Fig. 10. The mirror signage and AR animation system proposed in Kitamura et al. (2019). Figure reproduced with permission.



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 (Table 2).

As previously mentioned, AR can be used for research and training purposes (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 and Meehl, 1955; Kinateder and Ronchi, 2019; Pelargos et al., 2017; Ronchi et al., 2014). For training, the crucial question is whether or not the behaviour learned in training does translate into real-world behaviour (Duperrex et al., 2002). For the purpose of this review, we mostly focus on the research aspects although many of the criteria apply to both purposes.

For instance, current AR devices allow tracking of user position, orientation and input at around 60 Hz. 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

**Table 2**  
Overview of SWOT analysis.

Strengths	Weaknesses	Opportunities	Threats
<ul style="list-style-type: none"> <li>• Internal validity</li> <li>• Replicability</li> <li>• Safety of participants</li> <li>• Real-time feedback</li> <li>• Precise measurement</li> <li>• Low costs compared to other methods</li> <li>• Design flexibility</li> <li>• Independent of imagination abilities/willingness of participants</li> <li>• No simulator sickness compared to VR</li> <li>• Navigation in real-world environment</li> <li>• Reduced need for 3D models</li> <li>• Ease of transportation and setup (as of 2019)</li> </ul>	<ul style="list-style-type: none"> <li>• Need for confirmation/validation</li> <li>• Inter-individual differences in ease of interaction with AR</li> <li>• Technical limitations</li> <li>• No gold standard available yet; technology not mature</li> <li>• Costs for development and maintenance of AR software</li> <li>• Limited computational power of AR hardware</li> </ul>	<ul style="list-style-type: none"> <li>• Intuitive and natural user interfaces</li> <li>• Graphical developments</li> <li>• Multi-modal simulation and feedback</li> <li>• Usability for researchers</li> <li>• Exchange of 3D-scenes or experiments</li> <li>• Integration in BIM-based design and evacuation modelling</li> <li>• Proliferation of AR ready consumer devices</li> <li>• Access to cloud computing</li> </ul>	<ul style="list-style-type: none"> <li>• Failure to show validity</li> <li>• Failure to show training success in real world.</li> <li>• Misleading expectations</li> <li>• Technical obstacles</li> <li>• Privacy</li> </ul>

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 hardware and software can, therefore, recreate thus replicate any given AR experiment. 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 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).

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 et al., 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. 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” needs 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 into 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 high-end VR systems require hardware in addition to the HMD (e.g., computer and tracking devices). Thus VR hardware, as of 2020, 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 and 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 et al., 2018; Khalis and Mikami, 2018). Factors, such as sex, age or experience with AR, can influence how easily users may interact with AR technology (Ahmad et al., 2005)
- Technical limitations: AR technology is maturing rapidly. However, several current (2020) 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, OST AR displays are limited in the range of colour they can display and the level of brightness (Kun et al., 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 (also see discussion on tracking and recognizing in Section 1.1). 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 et al., 2016; Liang et al., 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 et al., 2016; Krichenbauer et al., 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 et al., 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 110° (the human binocular horizontal field of view spans 114°), whereas HoloLens 2 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 et al., 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 and 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 still have 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 in real life would be of limited use. Future research is needed to test how well 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 et al., 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 et al., 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 (Fig. 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 Fig. 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 (see Table 2) 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.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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