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A systematic review of the application of immersive technologies for safety and health management in the construction sector

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ABSTRACT

Introduction: The construction industry employs about 7% of global manpower and contributes about 6% to the global economy. However, statistics have depicted that the construction industry contributes significantly to workplace fatalities and injuries despite multiple interventions (including technological applications) implemented by governments and construction companies. Recently, immersive technologies as part of a suite of industry 4.0 technologies, have also strongly emerged as a viable pathway to help address poor construction occupational safety and health (OSH) performance. *Method:* With the aim of gaining a broad view of different construction OSH issues addressed using immersive technologies, a review on the application of immersive technologies for construction OSH management is conducted using the preferred reporting items for systematic reviews and meta-analysis (PRISMA) approach and bibliometric analysis of literature. This resulted in the evaluation of 117 relevant papers collected from three online databases (Scopus, Web of Science, and Engineering Village). *Results*: The review revealed that literature have focused on the application of various immersive technologies for hazard identification and visualization, safety training, design for safety, risk perception, and assessment in various construction works. The review identified several limitations regarding the use of immersive technologies, which include the low level of adoption of the developed immersive technologies for OSH management by the construction industry, very limited research on the application of immersive technologies for health hazards, and limited focus on the comparison of the effectiveness of various immersive technologies for construction OSH management. *Conclusions and Practical Applications:* For future research, it is recommended to identify possible reasons for the low transition level from research to industry practice and proffer solutions to the identified issues. Another recommendation is the study of the effectiveness of the use of immersive technologies for addressing health hazards in comparison to the conventional methods.

1. Introduction

The advancement of high-power computers and information technology has significantly enhanced the digitalization of fundamental processes within various industries, so as to boost reliability and reduce direct exposures of humans to harmful operations. One of the most prominent conveyors of such digital revolutions is industry 4.0. Industry 4.0 (also referred to as fourth industrial revolution) is the fourth industrialization process of the manufacturing sector, which involves the application of emerging technologies in the establishment and management of essential business processes (Cugno et al., 2021). The emerging technologies used in the revolution of the industrial sectors include robotics, big data and analytics, immersive technologies, additive manufacturing, autonomous operations, cloud computing, cyber-security and internet of things (Rüßmann et al., 2015). Industry 4.0 was pioneered in 2011 at the Hannover Fair event in Germany, which brought about the present-day generation of industrial revolution (Tay et al., 2018). Industry 4.0 is increasingly becoming highly appreciated by both practitioners and researchers within various industries, including the construction industry. It has been observed from literature that researchers in the construction industry have developed interests in the application of immersive technologies (ImTs), which is among the industry 4.0 technologies, in the management of construction activities. ImTs are technologies that are used for the simulation of the real-world environment and activities to deliver a sense of immersion in the simulated environment (Abbas et al., 2019; Khan et al., 2021). For example, a study conducted on the use of ImTs for facility management in

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the construction industry resulted into faster and easier access to information on the facility management phase when compared to the 2D blueprint-based facility management work (Chung et al., 2021). A study explored the innovative use of ImTs in tackling the shortage of young manpower in the electrical construction industry (Wen & Gheisari, 2021). The approach of storytelling using ImTs was adopted to narrate the success stories of the electrical trade in the construction industry to young students with the aim of inducing interest in the electrical construction industry to the students (Wen & Gheisari, 2021). Despite the advancement of industry 4.0 technologies in other sectors such as manufacturing industry (Zeba et al., 2021) and aviation industry (Vahdatikhaki et al., 2019), the uptake within the construction industry has been relatively low.

Studies have revealed that the construction industry is a very large industry, consisting of about 7% of global manpower and contributing about 6% of the world's gross domestic product (GDP) (Adami et al., 2021; Bhagwat et al., 2021). Despite its huge impact on employment and the global economy, the construction industry is inherently dangerous, thereby making it one of the most hazardous industries (Comu et al., 2021). The International Labour Organisation (ILO) evaluated the global annual record of fatal injuries in the construction industry to be over 100,000 (ILO, 2015). The construction industry has one of the highest records of occupational accidents and diseases, approximately 3.5 times the average rate of fatal injuries to workers than in all other industries (Health and Safety Executive, 2015) Also, the average rate of nonfatal injuries in the construction industry is approximately 1.5 times the average rate of nonfatal injuries in all industries (Health and Safety Executive, 2015). These unpleasant statistics clearly depict that the number and percentage of fatalities and injuries in the construction industry are immensely high and, therefore, require urgent intervention.

According to Park and Kim (2013), various studies have stated that the establishment and operation of consistent, appropriate, and well-planned safety management process, inspection, and training would have averted many of the accidents in the construction industry. The construction industry has, however, been very slow in incorporating digital tools for its safety management, despite the utilization of digital tools for its workflows (Afzal et al., 2021). Afzal et al. (2021) maintain that the conventional methods used for safety management in construction have their inadequacies in reducing the risks of accidents and fatalities and, therefore, recommends the use of technology-driven applications such as ImTs for construction safety management. Zhao et al. (2016) stated that the construction industry has a high turnover of employees as construction activities are highly work-intensive, which makes the management of occupational safety and health (OSH) more difficult than other industries. It has, therefore, become imperative to adopt an alternative method to the contemporary method used in tackling the OSH issues in the construction industry.

This study focuses on the application of ImTs as part of the emerging industry 4.0 technologies in addressing the OSH challenges in the construction industry. Academic researchers and industry practitioners may not have in-depth knowledge of the limitations and gaps in the application of ImTs for addressing OSH challenges in construction due to the overwhelmingly diverse and vast nature of studies in this area (Li et al., 2018). Li et al. (2018) discovered that ImTs have been explored and temporarily applied in various areas of OSH management such as training and education, hazard identification, risk perception of construction workers, and many more. It is noticed that virtual reality (VR), augmented reality (AR), and mixed reality (MR) are the trending realities in ImTs (Pavithra et al., 2020). VR, AR, and MR are the prominent ImTs in the construction industry (Alizadehsalehi et al., 2020; Khan et al., 2021). ImTs present an opportunity to reduce the rates of accidents on construction sites (Ahmed, 2019) thereby making them the cornerstone of study, as it is envisaged that a better understanding of their proficiency could significantly ease the adoption of ImTs for construction OSH management. However, at present, there is lacking within the literature a comprehensive understanding of the breadth of the role/potentials of ImTs in addressing OSH challenges in construction due to the diverse and vast nature of studies in this area (Li et al., 2018). Some reviews have been conducted on the application of ImTs (especially VR and AR for construction OSH management), but most of these reviews are often individualized owing to their focus on the application of just one or two ImTs on different OSH areas/topic in construction (Li et al., 2018). Other reviews have focused on the use of ImTs on a particular OSH area/topic in construction, such as for safety training (Gao et al., 2019). However, there is an underrepresentation of reviews that show the application of ImTs in various OSH areas, and various types of OSH hazards and conditions in construction.

The aim of this study is, therefore, to systematically review literature in order to: (1) investigate the current state of application of ImTs in construction OSH management; (2) investigate the challenges involved in the integration of ImTs in construction OSH management; and (3) propose recommendations regarding the application of ImTs in the management of OSH in construction OSH management.

The research questions that therefore directed this study are:

1. What is the current state of research on the application of ImTs for construction OSH management? In particular, what types of construction OSH areas, hazards, and conditions are addressed by ImTs in the academic literature?
2. What are the challenges/limitations and future research directions regarding the application of ImTs for construction OSH management?

The paper commences with an overview of the definitions and concepts pertaining to ImTs. This is followed by a detailed description of the systematic review approach applied for the study. Subsequently, the state of the application of ImTs for construction OSH management are presented, which highlights the OSH issues/areas and the types of OSH hazards and conditions addressed by ImTs in the construction industry. This is then followed by the challenges involved in applying ImTs for construction OSH management as seen in literature and consequently the recommendations for future works pertaining to research on the applications of ImTs for construction OSH management and finally, the conclusions.

2. Concepts and tools of immersive technologies

VR, AR and MR are the major types of ImTs that come under the umbrella term 'extended reality' and this can be regarded as a complete spectrum ranging from reality to virtuality (Khan et al., 2021). VR is a technology that is used for the development of computerized environment in which users feel isolated from the real world through the total immersion of the users in the computerized environment with the use of electronic devices such as head mounted displays (HMD), glasses, or the setup of multi-display screens (Davila Delgado et al., 2020). Users of VR technology can experience the sense of presence in a virtual environment with the use of a head-mounted VR device or the setup of two or three large projected screens referred to as cave automatic virtual environment (CAVE) (Shafiq & Afzal, 2020). VR has been used to expose learners to a particular work environment such as working at height experiences with realistic perception (Chander et al., 2021).

AR, another type of ImT, is the superimposition of digital information and images on the real-world environment to enhance the contextual perception of the environment of the users (Davila Delgado et al., 2020). AR is the amalgamation of the real-world scenario and computerized images and videos to produce a blended but improved view of the world (Ahmed, 2019). In contrast with VR, which absolutely comprises of a computerized model, AR blends the real and virtual worlds (Hallowell et al., 2016).

MR is the environment where real-world and digital objects coexist and interact in real-time (Hasanzadeh et al., 2020b). While AR involves the overlaying of virtual objects on real-world objects, MR involves the interactions between users and virtual objects in a real-world environment (Gao et al., 2019). Although ImTs are not new forms of technology, the industrial application of this technology is at its nascent stage as there has only been a routine and massive scale of use by the industry and the general public within the last five years (Mora-Serrano et al., 2021).

Based on the existing literature, the virtual environment can be created using computer software such as Unity game engine (Li et al., 2012b; Joshi et al., 2021; Mora-Serrano et al., 2021), Torque game engine (Zhao & Lucas, 2015; Zhao et al., 2016), Unreal game engine (Albert et al., 2014; Kim et al., 2021), and many more as shown in Table 1. There are various kinds of computer software that are developed for the modeling of virtual objects to be used in virtual environments, which will then be exported to game engines to be programmed using the required programming language. As depicted in Table 1, different game engines make use of different programming languages to program the various virtual objects in a virtual environment. The primary language of Unity game engine is C# (Joshi et al., 2021; Mora-Serrano et al., 2021), while the programming of modeled objects in Unreal game (Albert et al., 2014) and Torque 3D game engines is based on C++ (Zhao & Lucas, 2015).

An example of a computer software that is used for the modeling of virtual objects as seen in literature is Autodesk 3ds max (Sacks et al., 2013; Zhao & Lucas, 2015; Pooladvand et al., 2021). Albert et al. (2014) and Kim et al. (2021) used computer modeling software (i.e., Autodesk 3ds Max and Autodesk Maya) to draw out the virtual components to be used in the virtual environment developed using a computer game engine (i.e., unreal engine). Bhagwat et al. (2021) also used computer modeling software (i.e. Autodesk Revit and Trimble Sketchup) tools to create and model the virtual objects to be used in the virtual environment created by a computer game engine (i.e., Unity game engine). Furthermore, a computer modeling software (i.e., Blender) was used in a study to model a virtual environment consisting of a building under construction, its background (including the addition of colors and realistic textures to building components), as well as the construction workers for virtual animation and game scenarios (Pedro et al., 2016). Côté and Beaulieu (2019) developed a photorealistic environment by taking pictures of a road construction site and exported these pictures into a three dimensional (3D) reality modeling software (i.e., Bentley Context Capture) for assembly into photorealistic 3D mesh, prior to exporting into computer game engines.

Another example of a software tool used for the development of a virtual environment as observed in literature is the Photon Unity Networking (PUN). PUN cloud server was used for the implementation of a multi-user VR system by allowing multiple users to interact with each other in the same virtual environment (Shi et al., 2019). Users can see the movements of the avatars of other users in the virtual environment as the users regularly transmit their moving positions and body rotations to the other users in the same virtual environment (Shi et al., 2019). In a multi-user virtual environment, different users are connected via a multi-user platform, which includes a database that stores the true values for all pre-defined inputs of the users, including a knowledge and rule module for validation of the inputs of the users (Li et al., 2012a). The multi-user VR system, when turned on automatically, searches and connects to the server while an alternative method for connection to the server is for users to provide a suitable internet protocol (IP) address for manual connection (Li et al., 2012a).

While the roles of the aforementioned software tools in pioneering the creation of a typical VR environment are uncontested, there are also various hardware kits that are often utilized to mimic a sense of presence for human beings within such environments. To achieve representative sense of awareness, stimulating real-life senses such as sight, hearing, touch, smell, and taste are very essential (Suh & Prophet, 2018; Khan et al., 2021). These hardware kits provide the feeling of presence through vision, and they are generally known as VR headsets. VR headsets are stereoscopic head-mounted display units that use binocular vision to produce imaginary visions of depth (Habibnezhad et al., 2021). Examples of VR headsets as seen in literature include HTC Vive pro headset (Habibnezhad et al., 2021), Oculus head-mounted display unit (Xu & Zheng, 2021) and 3D stereo glasses (Sacks et al., 2015). These kits create sense of presence through vision as human beings need to wear them in order to immerse themselves into a virtual environment.

To further enhance sense of presence within typical virtual environments, the incorporation of sounds through simple stereo sounds or as spatial sounds was advocated in an earlier study by Meghanathan et al. (2021). Sounds of activities in the virtual environment can be included to enhance the feeling of presence, including the sound of footsteps or the engines of earth-moving equipment such as loaders. For example, a study conducted by Sacks et al. (2013) used a stereo sound system to enhance the sense of presence in the virtual environment by adding audio tracks of vehicles traveling, as well as some background sounds of typical construction sites, while Lu and Davis (2016) used computer and headphones to replicate similar sounds in their virtual environment. According to Lu and Davis (2016), the sounds common to most construction sites include those from the sound of vehicles (trucks), heavy equipment (tower cranes, excavators, loaders, drillers, mixers, etc.), physical interactions (talking, walking, etc.), and manual construction activities (creaking of woods, knocking of hammers, etc.). A further attempt to enhance the representativeness of real-life scenarios within virtual environments entailed incorporating the sense of feeling when users interact with virtual environments, which have been achieved via various enabling

Table 1
Examples of different game engines and their specifications.

	Game Engine				
	Unity	**Unreal**	**Torque**	**CryEngine**	**Microsoft XNA Game Studio**
Developer	Unity Technologies	Epic Games	GarageGames	Crytek	Microsoft
Operating System	Windows, Mac, Linux	Windows, Mac, Linux	Windows, Mac, Linux	Windows, Linux	Windows
Programming Language	C#	C++	C++	C++, C#, Lua	C#, Visual Basic.NET
Primary Usage	Game development	Game development	Game development	Game development	Game development

technologies. For example, a hardware controller (Nintendo Wii controllers) was used in a study conducted by You et al. (2018) to aid the users of a virtual masonry in grabbing, holding, and releasing concrete blocks while attempting to build a wall in the virtual masonry created using Unity 3D game engine. In a related study, a hardware controller (HTC Vive controller), was used by Adami et al. (2021) to enable the research participants to interact with virtual workers and objects in a VR-based training. Furthermore, Adami et al. (2021) used a treadmill (Virtuix Omni VR treadmill) to implement the navigation of demolition robots and teleoperate in different locations.

Finally, as observed from literature, examples of technological hardware tools used for the collection of data from participants of studies on the use of ImTs include Emotiv EPOC + EEG sensors, Omron electronic sphygmomanometer and, Tobii Pro X2-30 Hz eye tracker device. These technologies were used to collect electroencephalography (EEG) data (Emotiv EPOC + EEG sensors) of participants of a VR-based construction safety training, and to collect data on the blood pressure and heart rates (Omron electronic sphygmomanometer) of these participants in order to assess the physical and mental state of health of the trainees in a study conducted with a view of developing a VR-based system to curb the chronic health conditions suffered by construction workers due to overtime work (Huang et al., 2021). In addition, an eye tracker (Tobii Pro X2-30 Hz eye tracker device) was used in tracking the eye movements of participants of a study on virtual construction safety training to measure the concentration and adaptation levels of the participants (Comu et al., 2021).

3. Methodology

It has been observed that there is an underrepresentation of reviews that render a holistic view of the application of ImTs in various OSH areas, and various types of OSH hazards and conditions in construction. The lack of comprehensive academic documents makes it challenging for researchers to adequately examine the proficiency of all approaches under all scenarios at a glance. Additionally, the current study adopts the PRISMA-based systematic literature review (SLR) approach, which implies that there is a very logical approach to the definition of keywords, database selection, articles inclusion/exclusion, and research timeline, which makes it very easy for future researchers to determine the exact contributions as well as limitations of the study. The review was conducted based on the guidance from Page et al. (2021) on PRISMA methodology.

3.1. Review approach

The methodology adopted in this study was a SLR using PRISMA. A SLR can be defined as a review of literature that involves cogent collation of all evidences relevant to a particular field of study, with the aim of obtaining answers to a specific research question (Moher et al., 2016). There were four reviewers who screened each retrieved paper and these reviewers worked independently. In addition, a reference management system (Mendeley) was used to collate the response from each reviewer in real-time. The literature search was conducted using three online databases: Scopus (https://www.scopus.com), Web of Science (https://www.webofknowledge.com) and Engineering Village (https://www.engineeringvillage.com), owing to their technical prowess, diversity and size, especially with regards to industrial safety, technology, and construction. The keywords used for the search were divided into three fields: the first field focusing on the technology, the second field on the construction industry, and the third field on OSH as shown in Fig. 1.

The set of search strings applied to verify the title, abstract, and keywords of the papers collected from Scopus database is:

*(TITLE-ABS-KEY (“Industry 4.0” OR “Construction 4.0” OR “Augmented Reality” OR “AR” OR “*Virtual *Reality” OR “Mixed Reality” OR “MR”) AND TITLE-ABS-KEY (“Construction” OR “Construction Industry”) AND TITLE-ABS-KEY (“Occupational Health and Safety” OR “Occupational Safety and Health” OR “Safety and Health” OR “Health and Safety” OR “Safety” OR “Health”))*

The set of search strings applied to verify the title, abstract, and keywords of the papers collected from Web of Science (WoS) database is:

((TI=((“Industry 4.0” OR “Construction 4.0” OR “Augmented Reality” OR “AR” OR “Virtual Reality” OR “VR” OR “Mixed Reality” OR “MR”) AND (“Construction” OR “Construction Industry”*) AND (“Occupational Health and Safety” OR “Occupational Safety and Health” OR “Safety and Health” OR “Health and Safety” OR “Safety” OR “Health”))) OR (AB=((“Industry 4.0” OR “Construction 4.0” OR “Augmented Reality” OR “AR” OR “Virtual Reality” OR “VR” OR “Mixed Reality” OR “MR”) AND (“Construction” OR “Construction Industry”) AND (“Occupational Health and Safety” OR “Occupational Safety and Health” OR “Safety and Health” OR “Health and Safety” OR “Safety” OR “Health”)))) OR (AK=((“Industry 4.0” OR “Construction 4.0” OR “Augmented Reality” OR “AR” OR “Virtual Reality” OR “VR” OR “Mixed Reality” OR “MR”) AND (“Construction” OR “Construction Industry”) AND (“Occupational Health and Safety” OR “Occupational Safety and Health” OR “Safety and Health” OR “Health and Safety” OR “Safety” OR “Health”)))*

The set of search strings applied to verify the title, abstract, and keywords of the papers collected from Engineering Village (EV) database is:

((((“Industry 4.0” OR “Construction 4.0” OR “Augmented Reality” OR “AR” OR “Virtual Reality” OR “VR” OR “Mixed Reality” OR “MR”) WN KY) AND ((“Construction” OR “Construction Industry”)

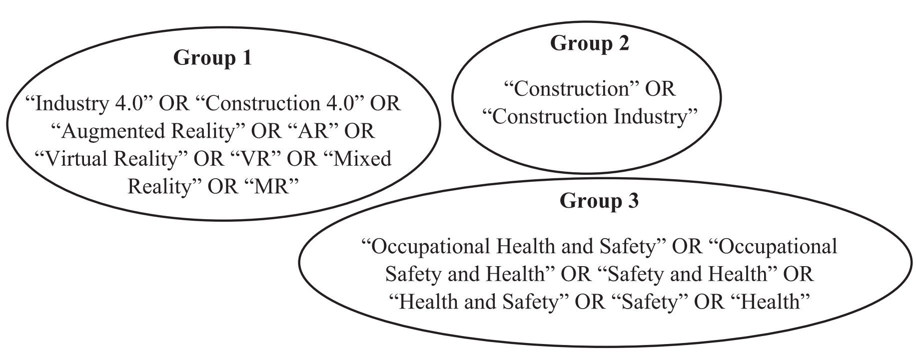

Fig. 1. Keywords for systematic literature review.

WN KY)) AND ((“Occupational Health and Safety” OR “Occupational Safety *and Health” OR “Safety and Health” OR “Health and Safety” OR “Safety” OR “Health”) WN KY))*

Fig. 2 shows a flowchart that depicts the different stages of the SLR process. The initial search yielded 967 publications from Scopus, 343 publications from WoS, and 1,040 publications from EV databases, making a total of 2,350 publications. The search strings were then limited to journal articles and reviews written in English language only. This is because journal articles and reviews are peer-reviewed and provide a more extensive and higher quality information when compared to other paper types such as conference papers and editorials (Farghaly et al., 2021; Hou et al., 2021). Furthermore, it has been observed that other document types (such as conference papers) when included in SLR usually complicate the analytical process and have very minimal impact on the results (Butler & Visser, 2006; Hosseini et al., 2018; Wuni et al., 2019). The total number of relevant publications after filtering the search string based on predefined inclusion and exclusion criteria was 953 publications, with 384, 204, and 365 articles from Scopus, WoS, and EV databases, respectively. These publications were then screened by their titles and abstracts as regards to the relevance of these publications to the scope of this study. The title and abstract screening of the publications filtered out 711 publica-

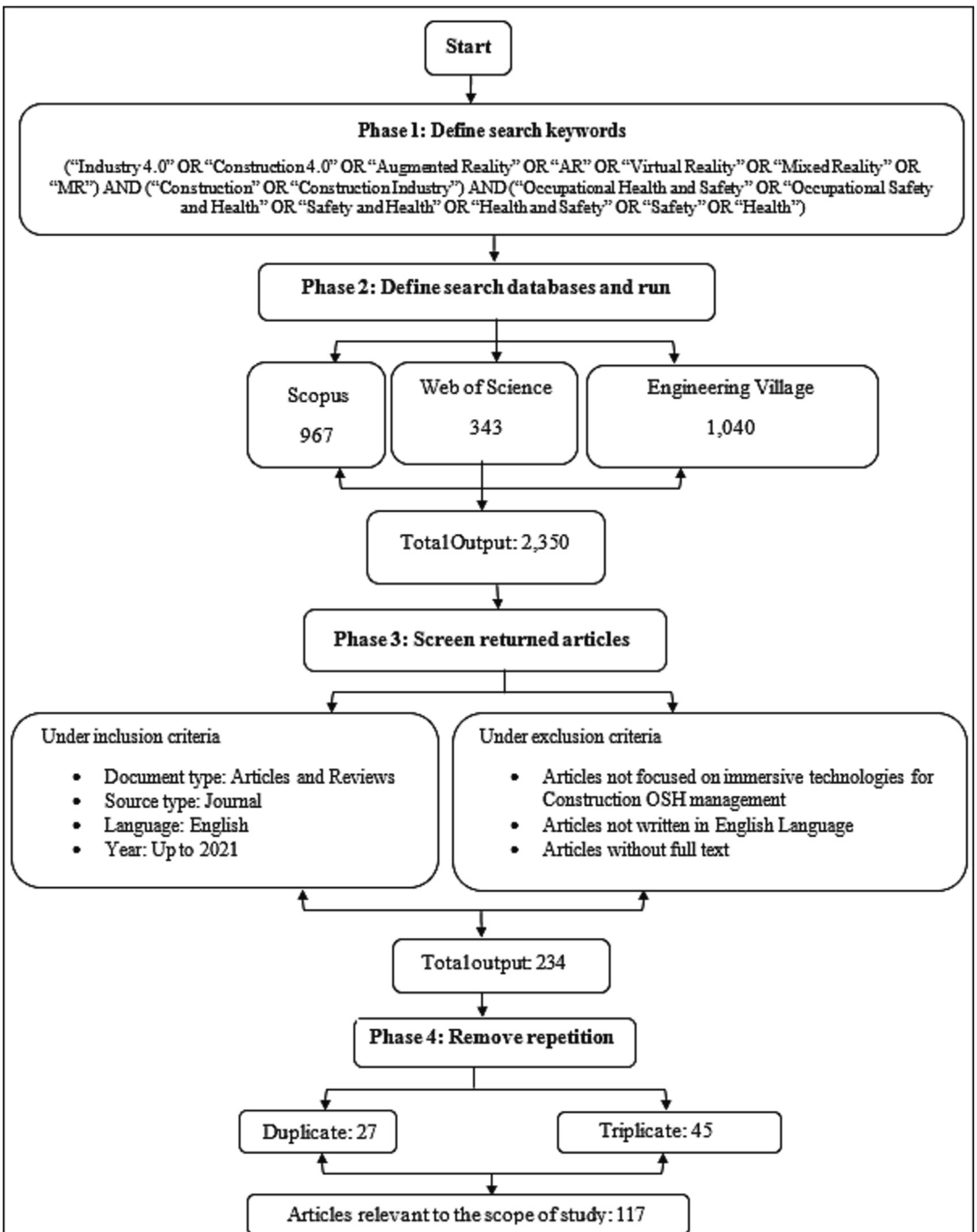

Fig. 2. PRISMA-based SLR flow diagram.

tions. For example, a publication by Chen et al. (2019) on the "*exploration on the difference in the taxonomic diversity and ecological exergy of the microbenthic faunal community before and after artificial reefs (AR) construction in artificial reefs habitat in the Pearl River Estuary, China*" was one of many rejected publications due to the lack of relevance of their contents.

Eventually, 245 publications were considered relevant across all databases, with a distribution of 79, 83, and 83 publications from Scopus, WoS and EV databases, respectively. The next stage of the filtration involved using a reference management system (in this case, Mendeley) to remove duplicate articles, which revealed 11 duplicates from EV database alone, because it comprises of 4 smaller but distinct database (namely, Compendex, Inspec, Geobase, and Georef). The exclusion of these 11 repeated articles further reduced the outputs from EV to 72 relevant publications and 234 publications in total. Furthermore, 45 triplicates from the three databases (14 duplicates from Scopus and WoS databases; 8 duplicates from Scopus and EV and 5 duplicates from WoS and EV) were identified and excluded accordingly. In order to enhance clarity and visibility, the Venn diagram shown in Fig. 3 depicts the distribution of the repeated articles across the databases through the intersection points. Once all duplicates and triplicates were removed, a total of 117 relevant papers were then retained for further detailed review. The SLR revealed that some previous studies attempted to investigate the application of ImTs (mainly VR, AR and MR) for managing OSH in the construction industry, with notable areas including hazard identification and visualization, training and education, risk perception assessment, and design for safety by using approaches such as literature review (Frank Moore & Gheisari, 2019), pilot study (Eiris et al., 2020), randomized controlled trial (Nykänen et al., 2020), case study (Guo et al., 2012), survey (Adami et al., 2021) and simulations (Lucena & Saffaro, 2020). However, the population and coverage of such studies are very limited as well as disproportionate to the poor OSH performance record within the construction industry. Additionally, there is a glaring underrepresentation of reviews that provide a holistic view of research activities related to the application of ImTs for the management of different facets of OSH with ImTs. The uniqueness of this study is further buttressed because none of the few existing reviews are systematic in nature, which makes it more challenging to verify robustness, especially with regards to the justifications for the included articles, search keywords, and timelines covered, which are vital for planning future research endeavors. Data extraction forms with the use of Microsoft Excel were used to obtain data from the research team. Details such as the year and location of study, aims of the study, OSH areas, hazards and conditions addressed by ImTs, the challenges associated with the use of ImTs for OSH management, and recommended future directions pertaining to applications of ImTs for construction OSH management were extracted using the data extraction form. One of the limitations of the review process is the focus of the information sources, which was limited to only Scopus, WoS, and EV. Another limitation is that only journal articles were reviewed.

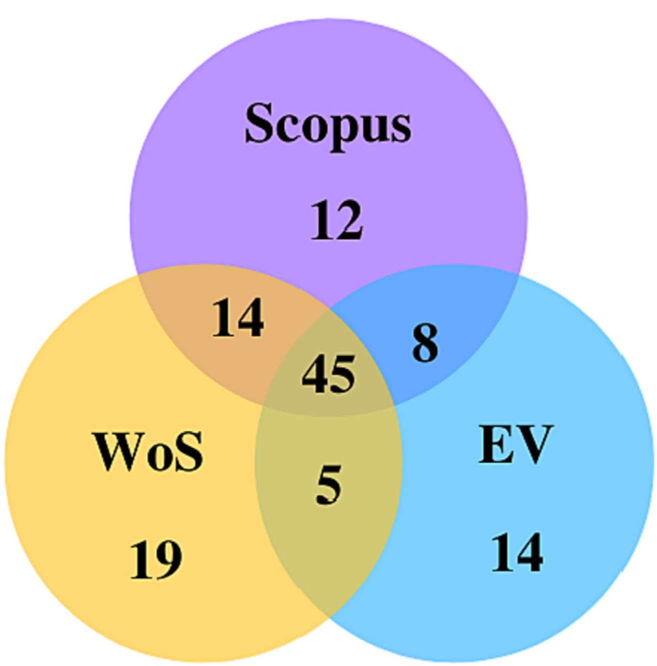

Fig. 3. Venn diagram of the distribution articles across databases.

3.1.1. Analysis

The initial stage of the analysis entailed observing the bibliometric data. To achieve this, the frequency of the included articles was analyzed based on year of publication, title of journal, location of study, and research method. The frequency analysis was facilitated using an analytic framework to enable the annotation of the included articles and extraction of relevant information pertaining to the research objectives.

For the effective analysis of the included articles, the SLR identified the locations of studies, aims and objectives of the studies, the research methods used by the study, the main findings of the study, other subsets of industry 4.0 technologies used to complement ImTs, the various challenges experienced in the applications of ImTs for construction OSH management, the different areas of construction OSH addressed by the applications of ImTs, the types of construction OSH hazards and conditions addressed by ImTs, the construction life cycle stage(s) addressed, and the hierarchy of control implemented. The SLR further identified future research areas pertaining to the applications of ImTs for construction OSH management.

4. Results and discussions

The results of a bibliometric analysis of the records obtained from Scopus, WoS, and EV databases is discussed, which shows the trends and patterns in the countries covered by the study, keywords, and co-authorships, as well as the inter-relationships between these variables. The distributions of publications per year, in different locations of study and the various source titles are also discussed with inferences made from these results. The usefulness of bibliometric analysis, especially with regards to SLR is that it makes the identification of peaks and troughs in data easy. It also enables researchers to match notable events and to aid research planning. The analytical framework adopted by this study is as shown in Table 2.

4.1. Bibliometric analysis

Bibliometric analysis is the mathematical analysis of literature and their properties, which include authorships, document type, and timeline and visualizes the physical aspect of the scientific research with the use of mapping tools (Akinlolu et al., 2020). A bibliometric analysis of articles is a very useful method of analysis as it shows the interactions amongst included articles, which makes it easier to understand how researchers have been able to establish an even distribution between quality, quantity, and the impact of such studies (Qiao et al., 2021). In addition, bibliometric analysis contributes to effective research planning and interdisciplinary collaborations. The bibliometric analysis of the included articles in this study was conducted using VOSviewer, as VOS-

Table 2
Analytical Framework.

Location (Country) of study
Aims/objectives of study
Main findings/outcomes
Complementary/linked industry 4.0 technology
Limitations/challenges related to application of ImTs
OSH management Issue/Area/Aspect addressed by ImTs
Type of OSH hazard addressed by ImTs
Type of OSH condition addressed by ImTs
Life cycle stage
Hierarchy of control
Limitations of the study

viewer is a known software for bibliometric analysis of data obtained from prominent literature databases such as WoS and EV (Qiao et al., 2021).

4.1.1. Mapping of the Co-occurrence of keywords

A network of keywords provides a coherent illustration of a specified sphere of knowledge, provides in-depth understanding of topics covered, and the cognitive inter-relationships between these topics (Darko et al., 2019). Thus, the mapping of the co-occurrence of keywords was generated using VOSviewer software. From the visualization generated by VOSviewer, the labels and circles display items in the visualisation network while the distance between each item denotes the strength of their relationships (Akinlolu et al., 2020). Hence, the larger the distance between any two given points within the network, the weaker the relationship between the corresponding items and vice versa. Typically, the link strength between two keywords is directly proportional to the thickness of their linkage lines and is estimated via the number of publications in which such keywords jointly appear (Darko et al., 2019).

The co-occurrence maps were generated based on a combination of keywords extracted from all the databases used for this SLR (i.e., Scopus, WoS, and EV). There are no standard rules for setting the frequency of the occurrence of the keywords (Wuni et al., 2019; Khan et al., 2021). To, however, accomplish the co-occurrence network of keywords, best practices as suggested by Chen and Song (2017), Oraee et al. (2017), Jin et al. (2018), and Hosseini et al. (2018) were used in this study. Consequently, a total of 2,100 keywords were extracted using the fractional counting method. With a minimum number of 5 co-occurrence of keywords, 73 keywords co-occurred, and 7 significant clusters were identified. Fig. 4 shows a network visualization map of the 7 co-occurring keyword clusters with 773 links and a total link strength of 339. The size of the circles representing a keyword depicts the number of times it appeared as an author keyword in the articles obtained in this study. As seen in Fig. 4, this therefore means that the keywords that have distinctly larger nodes than the rest of the keywords include *virtual reality, augmented reality, safety, construction safety, and construction*. Each cluster of keywords and grouped by keywords and each cluster indicates keywords that co-occur

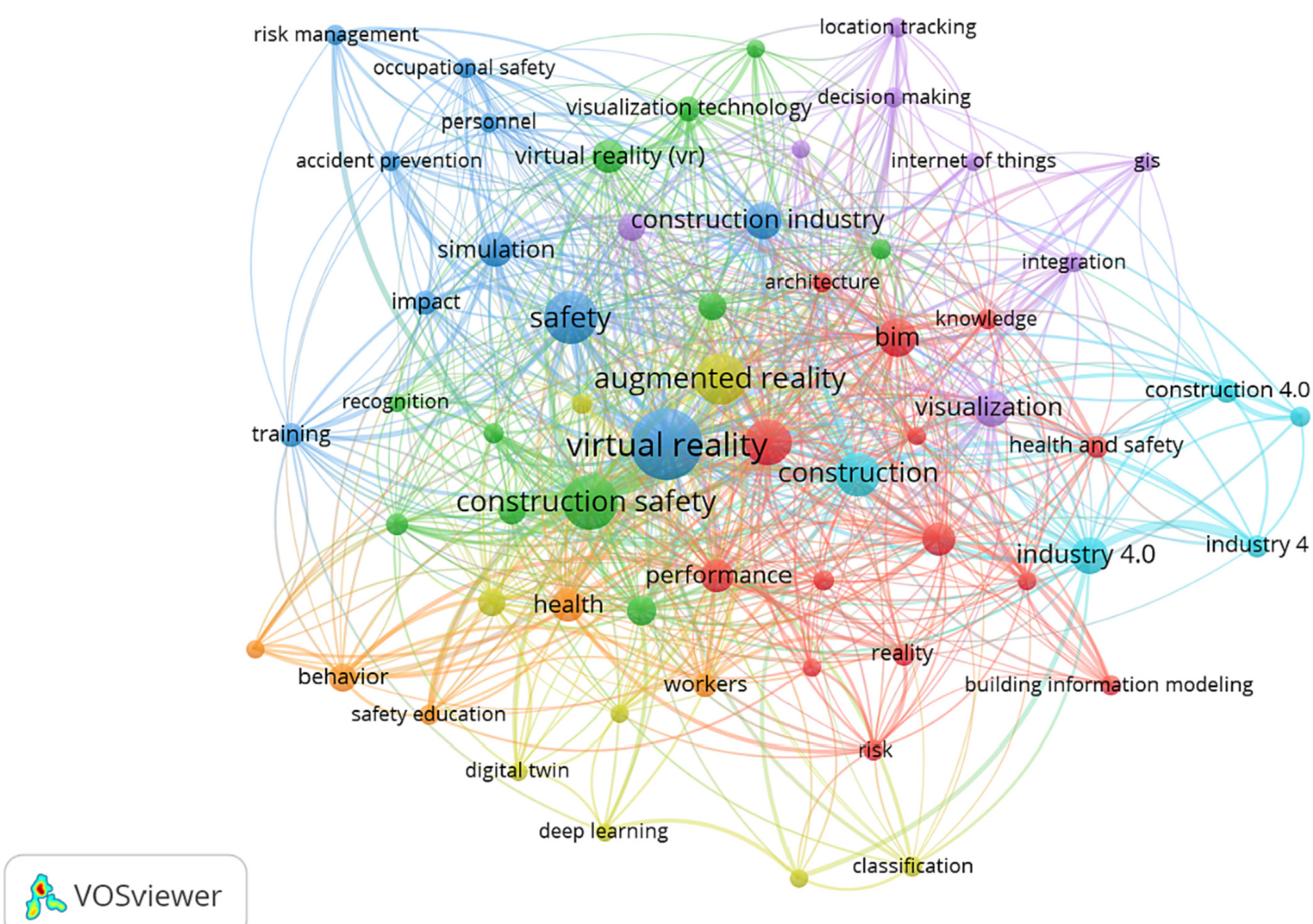

Fig. 4. Network of Co-occurrence of Keywords.

most frequently. This therefore means that keywords such as *safety, risk management, personnel, accident prevention and safety,* represented by the blue color, co-occurred frequently.

4.1.2. Mapping of co-authorship

Knowledge exchange, innovations and joint funding applications can be facilitated by the collaboration of researchers and institutions (Wuni et al., 2019). It is therefore necessary to visualize the network analysis of all the authors of articles, which assists in the identification of key collaboration in the research on ImTs for construction OSH management, which is presented in this section. Similarly, VOSviewer was used to conduct a network visualization of co-authorship, and the outcome is displayed in Fig. 5. This visualization included the mappings of the lead authors and their collaborators. This mapping was conducted to create a network of authors that had undertaken collaborative research on the applications of ImTs for construction OSH management. The type of analysis was set to "*co-authorship*" and the unit of analysis was set to "*authors*" in VOSviewer software, while the counting method selected was "*fractional counting.*" The minimum number of documents per author was set to 2 to filter authors that met the threshold. This generated 1,473 authors, including the lead and co-authors, with 134 meeting the set thresholds. The largest set of connected items was 35 items, as shown in Fig. 5. These connected items yielded 7 clusters, 63 links and a total link strength of 31. The overlay visualization co-authorship network shown in Fig. 5 shows that researchers such as Wang, I., Fang, X., Li, Z., and Yang, J. tend to collaborate more frequently.

4.1.3. Mapping of collaborations by country

In accordance with the aforementioned descriptions of keywords and authors network analyses, the collaboration network of countries within relevant study areas helps to recognize countries that are research-active (Darko et al., 2019). Hence, VOSviewer was again used to recognize the countries that are most influential in generating studies that focus on the applications of ImTs for construction OSH management. Similarly, the type of analysis selected was "*co-authorship*" with the unit of analysis set as "*countries*" and the counting method was "*fractional counting.*" In addition, the minimum number of documents of a country was set to 5 while the minimum number of citations of a country had a default setting of 0. The number of countries detected by VOSviewer software was 64 with 22 meeting the thresholds. The largest set of connected items was, however, 21 items as shown in Fig. 6, which shows the research-active countries in ImTs for construction OSH management. These connected items yielded 6 clusters, 60 links, and a total link strength of 82. As seen in Fig. 6, bigger nodes represent the United Kingdom, United States of America, China, and South Korea. It can also be seen from Fig. 6 that researchers and institutions from geographically close countries have a higher tendency to collaborate and cite the work of each other, such as: researchers from China, South Korea, Japan, and Taiwan in the Asian environment represented by the green cluster; Germany, Spain, UK, Norway, Portugal, and Italy from Europe represented by the red cluster; and the United States and Canada from North America represented by the blue cluster.

4.1.4. Distribution of publications per year

Fig. 7 shows the number of publications for every year a paper related to the scope of study of this review was published. The chart in Fig. 7 shows that there was little to no research on the application of ImTs for construction OSH management from 2000 and 2011 with no research conducted between 2002 and 2005 and between 2006 and 2010. Before 2012, the number of relevant papers published was not more than two papers, as shown in Fig. 7. There was a significant increase in the number of relevant papers published in 2012 with five more published papers than in 2011, with equal number of published papers in 2013. The significant increase in the number of papers in 2012 could be due to the launch of Industry 4.0 concept in 2011 (Yang & Gu, 2021). There was, however, a drop in the number of papers in 2014 from 2012 with two relevant papers published in 2014, with a significant increase again in 2015 and 2016 as seven relevant papers were published in both years. A final decline in the number of relevant published papers occurred in 2017 with five relevant papers published in 2017, which was less than the seven papers published in 2016. The decline in the number of papers could be due to the high proportion of publications on industry 4.0 focusing on engineering, communication, and business process management during this period (Petrillo et al., 2018). The distribution, however, showed an increasing trend of publications from 2017 through 2021, with 32 relevant papers published in 2021 in comparison to the 5 relevant papers in 2017, with the number of publications recorded for 2018, 2019, and 2020 being 9, 14, and 20, respectively.

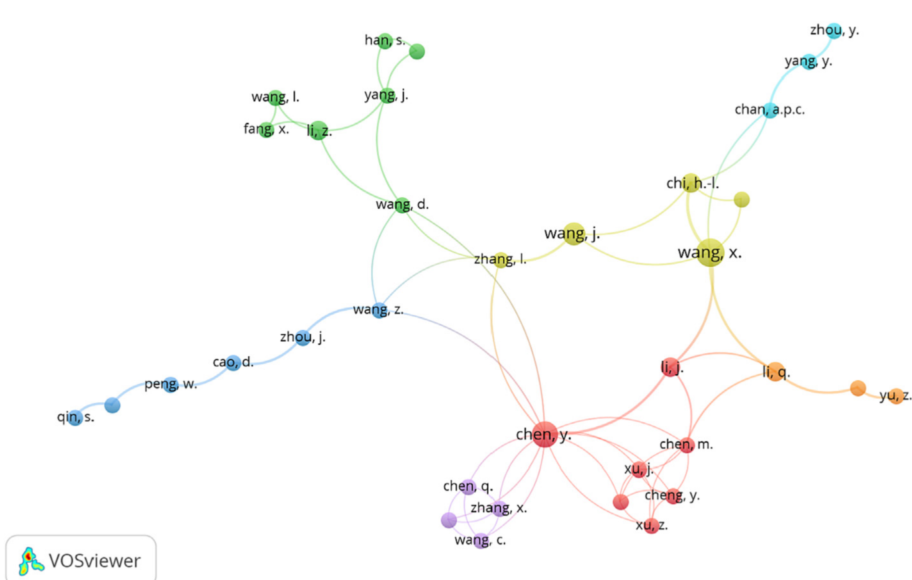

Fig. 5. Network of co-authorships.

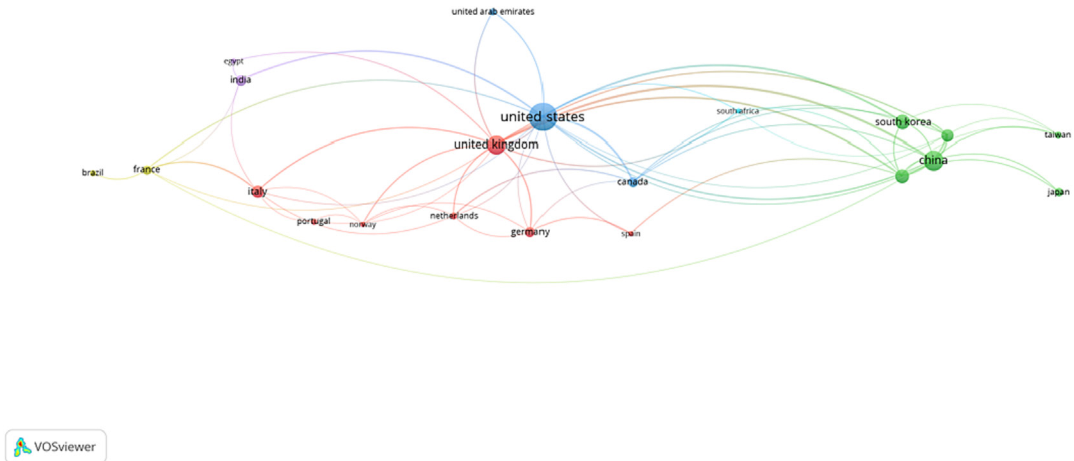

Fig. 6. Network of Collaborations by Country.

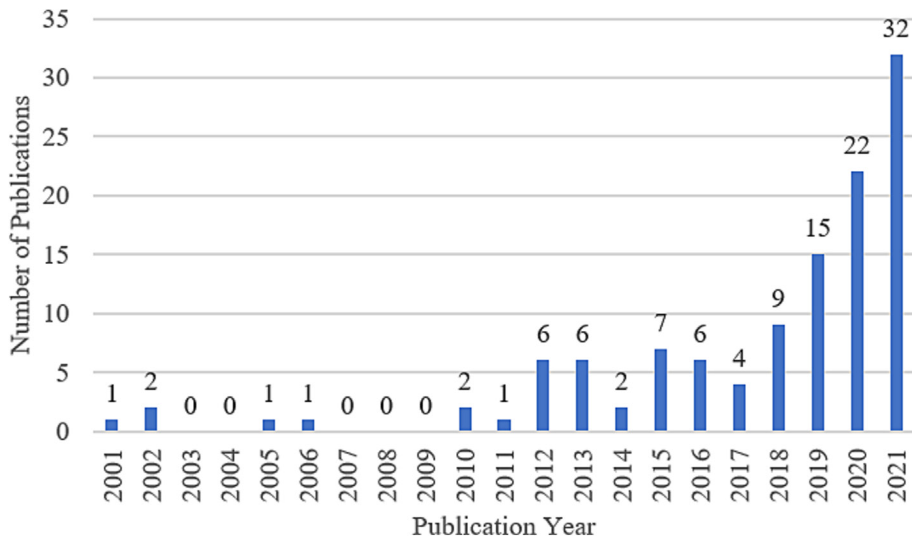

Fig. 7. Distribution of publications per year.

Overall, there has been an increase in the interest of researchers on the application of ImTs for construction OSH management as 32 papers were published in 2021, which is huge progress when compared to the single paper published in 2000. One of the 32 papers published in 2021 is 'Classification of construction hazard-related perceptions using: Wearable electroencephalogram and virtual reality' (Jeon & Cai, 2021), which investigated the feasibility of hazard identification on construction sites with the use of a developed EEG classifier based on experiments conducted in an immersive VR environment in order to address the continuous emergence of new hazards as construction activity progresses. Another study conducted in 2020 titled 'How Sensation-Seeking Propensity Determines Individuals' Risk-Taking Behaviours: Implication of Risk Compensation in a Simulated Roofing Task' (Hasanzadeh et al, 2020a) was conducted with a MR roofing simulation to understand the reason the level of safety intervention tends to make construction workers modify their risk-taking behavior. A significant study amongst the literature published in 2019 is the human-subject experiment conducted using a multi-user VR system and motion tracking device to investigate the social learning behavior of construction workers in the paper titled 'Impact assessment of reinforced learning methods on construction workers' fall risk behaviour using virtual reality' (Shi et al., 2019).

4.1.5. Distribution of publications by location of study

Fig. 8 shows the number of articles across different locations of the world on the application of ImTs for construction OSH management. This was obtained from the institutional address or affiliation of the corresponding authors of the included publications. As seen in Fig. 8, different studies on the application of ImTs for construction OSH management were conducted in at least 27 countries around the world between 2001 and 2021, with the United States conducting the highest number of studies with 44 publications. This indicates that the United States is the biggest contributor to the studies on the applications of ImTs for construction OSH management. The United Kingdom is the second biggest contributor to the applications of ImTs for construction OSH management with nine publications, while Australia, China, and Hong Kong contributed seven publications each. This confirms that there are more research studies from European, American, and Asian countries on digital technologies as countries from these continents are ranked the most digitally innovative countries in the world (Martínez-Aires et al., 2018; Vukšić et al., 2018; Aghimien et al., 2020; Akinlolu et al., 2020; Institute of Management, 2021). In addition, Korea had six publications, while Canada and South Korea had four publications each, with Italy and UAE having three publications each. Finland, Iran, Israel, Malaysia, Spain, and Sweden contributed

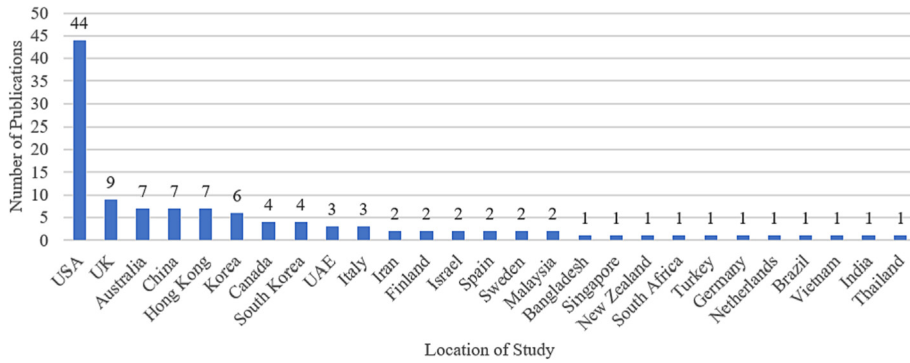

Fig. 8. Distribution of Publications per Location of Study.

two publications each, while Bangladesh, Brazil, Germany, India, Netherlands, New Zealand, Singapore, South Africa, Thailand, Turkey and Vietnam contributed a single paper each.

One of the 44 papers conducted in the United States which is titled 'Predicting workers' inattentiveness to struck-by hazards by monitoring bio signals during a construction task: A virtual reality experiment' (Kim et al., 2021) was based on a feasibility study involving the combination of the use of eye tracking sensors, EEG devices, and machine learning techniques in an immersive virtual environment to predict when construction hazards will be successfully recognized. In another UK-based study conducted by Bosché et al. (2016), the authors aimed to address the challenges of construction safety training by developing a novel mixed reality system that allows training within challenging site conditions to eradicate OSH risks in the construction industry.

4.1.6. Distribution of publications by journal titles

Table 2 presents the distribution of the articles included from all three databases by the titles of journals. The SLR revealed that 53 journals have published research and review articles related to the application of VR, AR, and MR for OSH management in the construction industry. As depicted by Table 3, 'Automation in Construction,' 'Journal of Construction Engineering and Management,' and 'Advanced Engineering Informatics' are the three journals with the most publications with 19, 9, and 6, respectively. 'Construction Innovation,' 'Engineering, Construction and Architectural Management,' and 'Safety Science' recorded equal number of articles with five each. Each of these aforementioned journals have produced several articles that have immensely contributed to the emergence and understanding of the concepts of technology-driven OSH management within the construction industry. For instance, the article titled *"Comparison of ironworker's fall risk assessment systems using*

Table 3
Distribution of Published Papers by Journal Titles.

Journal Title	Number of Published Papers
Automation in Construction	19
Journal of Construction Engineering and Management	9
Advanced Engineering Informatics	6
Construction Innovation	5
Engineering, Construction and Architectural Management	5
Safety Science	5
Journal of Applied Science	4
Buildings	3
Construction Management and Economics	3
International Journal of Environmental Research and Public Health	3
Journal of Computing in Civil Engineering	3
Journal of Information Technology in Construction	3
Sustainability	3
Accident Analysis and Prevention	2
Applied Ergonomics	2
ArXiv	2
International Journal of Engineering Education	2
Procedia Engineering	2
Visualization in Engineering	2
Advances in Civil Engineering, Cognition, Technology & Work, Computers and Education, Education Sciences, Electronics, Engineering Construction and Architectural Management, Engineering Journal, Ergonomics, Facilities, Frontiers in Robotics and AI, IEEE Multimedia, IEEE Transactions on Visualization and Computer Graphics, Infrastructures, Injury Prevention, International Journal of Construction Management, International Journal of Engineering, Transactions B: Applications, International Journal of Injury Control and Safety Promotion, International Journal of Occupational Safety and Ergonomics, Journal of Building Engineering, Journal of Civil Engineering and Management, Journal of Civil Engineering Education, Journal of Intelligent & Robotic Systems, Journal of Management in Engineering, Journal of Mechanical Science and Technology, Journal of Professional Issues in Engineering Education and Practice, Journal of Safety Research, Journal of Systems Architecture, Organization Technology and Management in Construction, Proceedings of the Institution of Civil Engineers: Civil Engineering, Proceedings of the International Conference on Information Visualisation, Safety, Structure and Infrastructure Engineering, Visual Computer, Workplace Health & Safety	1
Grand Total	**117**

an immersive biofeedback simulator" (Habibnezhad et al., 2021) is a significant paper identified from the 'Automation in Construction' journal, which evaluated the fall risk of ironworkers with the use of a reliable and responsive VR simulator.

Another paper from the 'Journal of Construction Engineering and Management' is "*Productivity-Safety Model: Debunking the Myth of the Productivity-Safety Divide through a Mixed-Reality Residential Roofing Task*" (Hasanzadeh & de la Garza, 2020), whereby an immersive mixed reality environment was used to simulate a roofing task, so as to investigate whether the alleviation of task-demands resulting from safer construction site conditions actually causes fall risks to be underestimated. Similarly, a notable publication from 'Advanced Engineering Informatics' journal titled "*Evaluating the attitudes of different trainee groups towards eye tracking enhanced safety training methods*" (Comu et al., 2021) monitored the eye movements of construction safety trainees during VR-based safety training method and traditional safety training methods to understand the attitudes as well as the knowledge retention levels of the trainees toward the training provided.

4.2. State of application of immersive technologies for construction occupational safety and health management

A typical construction site is an embodiment of highly diverse workers from different organizations, with different skill levels and safety cultures. In addition to inherent risks posed by this diversity, numerous high-risk and often complex tasks must also be performed in parallel by different workers within close proximities, which in turn heightens the overall likelihood of unwanted events (Hou et al., 2021). Although conventional OSH management regimes such as PPEs, safety trainings, toolbox talks, and safety inductions are well-established at construction sites, their proficiencies are still undermined by the poor safety record across the industry. It is therefore essential to further explore how recent advancements in technology can be used to strengthen existing approaches, of which industry 4.0 technologies seems to offer complementary alternatives. However, prior to implementing any new approaches, it is imperative to adequately understand the limitations of the existing body of knowledge. Therefore, this SLR focuses on how ImTs as a suite of industry 4.0 has been applied in construction OSH management and how other industry 4.0 technologies complement ImTs in construction OSH management.

4.2.1. Occupational safety and health issue/area addressed by immersive technologies

The popular OSH areas that the reviewed literature focused on are hazard identification and visualization, training and education, risk perception and assessment, design for safety, and general safety. These areas were selected based on the analytical framework adopted in this study as shown in Table 2. The distribution of these areas across the reviewed articles is shown in Fig. 9.

a. Hazard identification and visualization

The uniqueness of every construction project makes it difficult to identify all possible OSH risks, but the use of immersive virtual reality environment can provide a visualization of construction site conditions, thereby making hazard identification easier before commencement of project (Azhar, 2017). Hazard identification is essential for both the safety management team and construction workers (Li et al., 2012b). Shafiq and Afzal (2020) noted that it has become necessary to make use of VR for the improvement of safety in construction, as the conventional methods of instilling effective and practical hazard identification safety knowledge is inefficient. Shafiq and Afzal (2020) also noted that a CAVE system can be used for identification of hazards. Examples of hazards that can be found in the construction industry are: dismantling of tower crane before workers leave the area; working on construction activity without wearing appropriate personal protective equipment (PPE); and building platforms without appropriate fencing (Li et al., 2012b).

One of the identified studies on hazard identification was by Kim et al. (2017), which proposed a vision-based hazard avoidance system for the prevention of accidents by allowing workers to identify hazards through the rendering of augmented hazard information on a wearable device. However, the information rendered by this AR system (consisting of a vision-based site monitoring module) rendered the construction site in a planar form, thereby limiting the identification of other important hazards by workers (Kim et al., 2017). An approach that can be used to address the planar view of the construction sites was observed in a study by Eiris et al. (2018), which involved the development of an augmented 360 degree panorama of reality (PARS) that provides a true-to-reality view of construction sites for effective hazard identification. Subsequently, the participants of this study experienced ease in

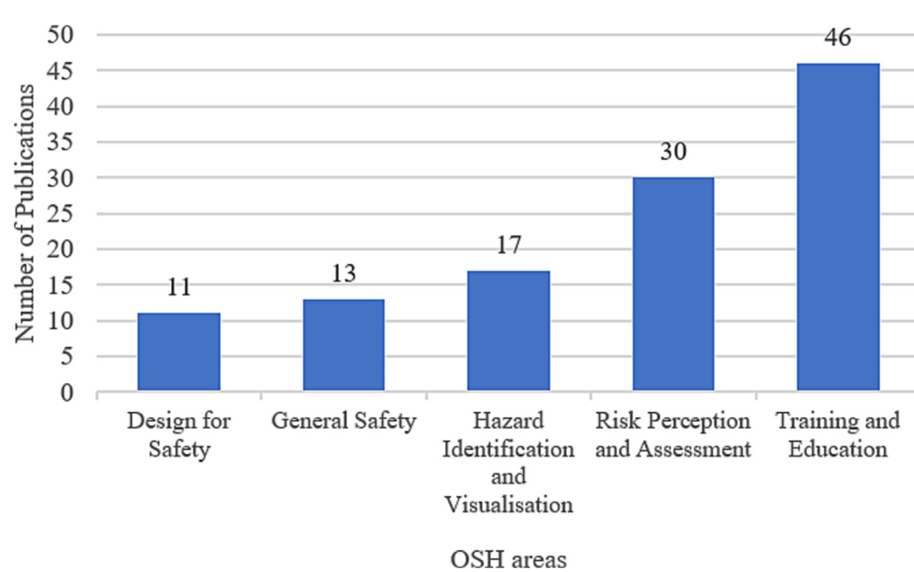

Fig. 9. Distribution of publications within construction OSH areas.

the operation of the system while it assisted them to locate hazards in the panoramic scenes (Eiris et al., 2018). In another dimension, the planar view of construction sites by the vision-based avoidance system can also be addressed with the approach used in a study by Afzal and Shafiq (2021) which involved the application of 4-dimensional (4D) building information models (BIM) and VR. It was observed that VR and 4D-BIM was used for the 4D simulation of construction sites (easy to use and provided the real-life experience of a construction site without actually being in a site), which assisted in hazard identification of workers (Afzal & Shafiq, 2021). A similar study conducted by Teizer et al. (2013) presented a 3-D view of primarily steel erection tasks with the application of location tracking sensors and VR for the effective identification of hazardous activities by steel workers, and it resulted in the effective identification and visualization of hazards. In addition, three case studies conducted by Azhar (2017) demonstrated that contractors can use 4D simulations, BIM models, and VR environment to visually identify hazards. This could assist in the development and communication of plans for mitigating the identified hazards amongst construction workers (Azhar, 2017). This could be more effective in addressing hazards, especially when compared to two dimensional (2D) drawings, because these digital tools closely simulate actual jobsite conditions (Azhar, 2017).

Another alternative approach in the application of ImTs for hazard identification and visualization was observed in a study by Lucena and Saffaro (2020), which involved the exploration of a virtual construction site by construction managers. The construction managers had to mention the hazards they identified to the instructors as the VR technology used provided visual stimuli to them, thereby making it easier to detect dangerous situations intuitively (Lucena & Saffaro, 2020). A similar approach involving the walkthrough of workers in a virtual construction site for hazard identification was adopted in a study conducted by Hadikusumo and Rowlinson (2002). The workers also selected appropriate precautions to the identified hazards for the prevention of accidents (Hadikusumo & Rowlinson, 2002).

b. Training and education

Training and education is a crucial aspect of OSH management, owing to proven instances whereby attitudes, personal characteristics, workplace climates, and organizational cultures have been enhanced through knowledge. Ahmed (2019) noted that safety training and education is a key factor in the promotion of a safe and healthy working environment in the construction industry. One of the most effective ways of improving construction OSH performance is by safety training (Li et al., 2012b). This is perhaps why 39% of studies focused on addressing construction safety training using ImTs as depicted in Fig. 9. Despite the significant importance of safety education for the improvement of safety performance in the construction industry, there is very limited emphasis on safety within the curricular of most of the programs delivered at mainstream institutions of higher learning (Pham et al., 2018). Xu and Zheng (2021) attributed the occurrence of preventable accidents in the construction industry to a lack of experiential training on OSH and highlighted that the occurrence frequency of accidents can be immensely reduced by enhancing the safety awareness of construction site workers through VR-based technologies. The conventional methods of safety education at the few tertiary institutions that offer them have been termed inefficient, due to their inability to adequately replicate or mimic real-life experiences (Le et al., 2015). The conventional methods of safety education consist mainly of lectures, presentations, and video training, which are economical but not necessarily fostering employee engagement and/or knowledge retention. On-site or on-the-job equivalents to safety training have been described as far more engaging, but their huge costs and potential to interrupt industrial operations make them the least preferred option by some employers (Joshi et al., 2021). This is perhaps the reason for the upward trend in publications related to technology-enhanced OSH management as depicted by Fig. 7. For example, Le et al. (2015) conducted a study that indicated that the developed prototype of a collaborative VR-based system for construction safety education through dialogic learning and social interaction in a virtual 3D environment has great potential to improve construction safety education. Le et al. (2015), however, recommended that a study on the application of the integration of collaborative VR technology and AR for construction safety education should be considered. Another study conducted by Le et al. (2015) then proposed a framework that combines mobile-based VR and AR to create virtual scenarios of real accident occurrences for delivering safety education to students and discovered that the integration of VR and AR with mobile computing can address the limitations of the conventional construction safety education. Bhagwat et al. (2021) also conducted a study on mobile-based VR system that was developed as a game-based safety module. Bhagwat et al. (2021) realized that students preferred the mobile VR system because it provided realistic and immersive experience, while construction professionals prefer a virtual tour-based safety module because of its ease of operation, cost-effectiveness, and time savings. Getuli et al. (2021) used a different approach as the integration of building information modelling (BIM) and VR for construction safety training was proposed. A safety training protocol based on BIM-enabled VR activity simulations was used in tackling the complexities associated with rendering safety trainings. The integration of BIM and VR for safety training by Getuli et al. (2021) addressed the technological aspects, thereby allowing for a coherent flow of information from the BIM environment to the VR simulated environment, and it also alleviates some of the methodological issues, especially those related to aiding decisions on training needs analysis and scheduling.

Xu and Zheng (2021) developed a VR safety training platform that is comprised of a 3D modeling stage, VR environment rendering process, and the training system program design. It was discovered that the developed safety training platform was more effective in the training of workers when compared to the conventional safety training methods, but the platform could not enable free navigation of the workers in the real world during the training session, thereby reducing the realism of the immersive experience (Xu & Zheng, 2021). This navigation limitation could, however, be addressed by the method used by Adami et al. (2021) which involved the use of a VR treadmill in the virtual dynamic construction site for navigation of workers. Seo et al. (2021) focused on the use of VR technology for the implementation of an experiential safety education system in the electrical construction trade. The study indicated that the VR-based safety education system for electrical construction site workers could improve their learning outcomes, and provides an environment for learning in risky scenarios that could be difficult in lecture-based methods (Seo et al., 2021). Joshi et al. (2021) focused on a different construction trade and developed a VR safety training module for the precast concrete industry with the aim of assisting precast concrete industry workers in understanding safety protocols more accurately and to avoid more accidents. Joshi et al. (2021) discovered that the VR training module made workers highly motivated, had the potential to help workers retain and understand more information, and also had the potential to reduce the number of accidents on sites. A study conducted by Nykänen et al. (2020) revealed that VR-based construction safety training has stronger impacts on self-confidence, safety motivation, and safety-related outcome expectancies when compared to conventional lecture-based alternatives.

c. Design for safety

Construction sites are very complex and dynamic work environments, which makes the processes required for ensuring the safety of their designs extensive but crucial for averting accidents (Côté & Beaulieu, 2019). In recent times, concepts such as design for safety (DfS) have gained significant traction toward ensuring that construction designs prioritize accident prevention (Manu et al., 2019). Design for safety is also known as prevention through design, safety through design, and safety by design (Farghaly et al., 2021).

Designers can play a huge role in the improvement of construction OSH management with VR, a very useful tool, used in assisting designers make appropriate decisions leading to safety during the execution of construction works (Sacks et al., 2015). Sacks et al. (2015) emphasized the usefulness of VR to OSH management in construction, especially their ability to support the decision-making process of designers in the execution of construction work by conducting pilot tests on designers and construction managers who both have knowledge on safety issues in design and construction. The study conducted on designers and construction managers by Sacks et al. (2015) involved the interaction of these participants in a virtual construction site and it was discovered that dialogue makes safety issues in designs more identifiable and clearer, especially for designers. In another closely related study, Hadikusumo and Rowlinson (2002) proposed a design-for-safety-process (DfSP) that integrates VR functions, virtual construction components and processes, and DFSP database. The DfSP allows construction practitioners to perform a walk-through of the virtual environment equivalent to their construction sites to proactively identify inherent hazards, so that appropriate mitigating measures can be implemented to avert catastrophic accidents (Hadikusumo & Rowlinson, 2002).

Yu et al. (2019) focused on combining the features of VR and AR technologies with BIM, big data processing terminals, and wearable devices for issuing reports on the dynamic safety predictions and danger warnings. Another study focused on the integration of BIM with emerging digital technologies such as global positioning system (GPS), laser scanning, sensors, VR, AR and photogrammetry for construction safety and high-rise buildings with promising results of the integration of BIM with digital technologies for construction safety in high-rise buildings (Manzoor et al., 2021). Another study presented the potential of using virtual design construction (VDC) tools such as VR, AR, BIM, and geographic information systems for the improvement of safety on construction sites in Gulf Cooperation Council (GCC) countries (Shafiq & Afzal, 2020). The study indicated that the design of emergency and evacuation plans and fall-hazard prevention strategies are the most effective applications of the VDC tools in the improvement of construction site safety (Shafiq & Afzal, 2020).

d. Risk perception and assessment

An immersive MR environment was developed and integrated with real-time head and ankle tracking sensors to monitor the reactionary behavioral responses of building construction students with industry experience during the execution of roofing tasks, under three experimental scenarios: (1) task with no fall arrest system; (2) task with fall-arrest system; and (3) task with fall-arrest system and guardrail (Hasanzadeh et al., 2020b). Based on the risk assessment conducted on the participants of this study while installing asphalt shingles, Hasanzadeh et al. (2020b) observed that the safety complacency of participants increased as the level of safety protection offered increased (i.e., risk-averseness of participants reduced as they moved from Scenarios (1) – (3)). In another study, Pooladvand et al. (2021) aimed to enhance safety inspections and planning routines of on-site lifting operations by proposing a framework that uses VR technology to proactively assess the risks involved in routine lifting operations of mobile cranes prior to the commencement of actual tasks to better improve the understanding of inherent failure modes associated with lifting of heavy modules. The outcomes of the assessment broadened the perception of risk and the lifting process of users of the mobile crane in the virtual jobsite created with a computer game engine (Pooladvand et al., 2021).

The risk perception of forklift operators during the operation of forklifts was assessed with the use of a VR forklift simulation model for various subtasks such as driving, loading, unloading reversing, and turning (Choi et al., 2020). It was revealed that the different subtasks affect the level of risk perceptions of the forklift operators differently, depending on the complexity of such tasks. Choi et al. (2020) then suggested the use of additional control measures such as sensing devices and situational signifiers for the improvement of the risk perception of forklift operators. Another study involved the use of immersive MR construction site environment and real-time head and ankle-tracking sensors to simulate a roofing activity in order to monitor and assess the risk perception of workers while performing roofing activities with the use of fall protection (Hasanzadeh et al., 2020b). Upon the conclusion of the study, Hasanzadeh et al. (2020b) asserted that roofing workers perceive less risk because the usually use fall protection, which allows them to be more reckless when performing roofing activities and take more risks.

e. General safety

Akinlolu et al. (2020) conducted a bibliometric review on industry 4.0 technologies including VR for construction health and safety management and the review revealed that the application of these technologies has improved the health and safety issues in the construction industry. It was also observed that there is an underrepresentation of the application of industry 4.0 in Africa in the literature when compared to other continents (Akinlolu et al., 2020). Li et al. (2018), however, conducted a critical review focusing mainly on VR and AR in addressing construction safety issues in academic studies. It was discovered that academic studies on VR and AR for construction safety have been conducted from various views, including safety enhancement mechanisms and technology characteristics with proven efficiency of VR and AR in the general construction safety areas (Li et al., 2018).

4.2.2. Types of occupational safety and Health hazards addressed by immersive technologies

This SLR has revealed that the main types of OSH hazards addressed by the use of ImTs are struck-by hazards (Oh et al., 2019), electrocution (Zhao & Lucas, 2015; Zhao et al., 2016), working at height (Habibnezhad et al., 2021), caught-in/between (Pham et al., 2019), and slips/trips (Afzal & Shafiq, 2021). This is perhaps why several studies are seeking remedies through various initiatives, including the development and evaluation of advanced safety algorithm to tackle collisions between an excavator on site and nearby workers using real-time simulations with VR (Oh et al., 2019). The VR technology that simulated excavator movement showed that the developed advanced safety algorithm can prevent workers from getting struck by excavators, thereby reducing fatal accidents on construction sites (Oh et al., 2019). Zhao and Lucas (2015) proposed the use of VR simulation for safety training to reduce fatalities and accidents caused by electrocution, owing to previously reported effectiveness of VR approaches for construction safety trainings. The leading cause of injuries and deaths on construction sites is falling from height and this prompted Habibnezhad et al. (2021) to examine a VR simulator that integrates several tracking devices attached to key parts of the body for assessment of fall risk of ironworkers. This is perhaps why the number of publications that have focused on fall hazard as depicted in Fig. 10 is high. Alternatively, in order to address fall hazards, Bosché et al. (2016) conducted a study on how to make use of MR technology to provide exposure on conditions surrounding working at height to trainees, with positive feedback from the test subjects regarding the effectiveness of the MR system on the preparation of trainees for working at height conditions that they will later experience in a real construction site.

The experiments were conducted on 12 healthy adults and highlighted that a more effective performance is achievable through the VR simulator, especially in the upper-limb stability assessment of workers at height when compared to traditional VR systems (Habibnezhad et al., 2021). Pham et al. (2019) proposed an interactive augmented photoreality (iAPR) platform that provides safety education for construction students on hazards such as caught-in/between, electrocution, struck-by and fall. The proposed iAPR platform showed effectiveness in enhancing construction hazards investigation knowledge and skills. The effectiveness of a four-dimensional (4D) BIM and VR system developed for the simulation of construction site to train a multilingual construction crew on construction safety, with emphasis on the avoidance of slips, trips, and falls was also evaluated by Afzal and Shafiq (2021).

4.2.3. Types of occupational safety and Health conditions addressed by immersive technologies

Typical construction sites are characterized by different classes of OSH hazards, which may impact the safety, health and well-being of employees in different ways. For instance, some construction workers are exposed to different levels of noise, which may lead to hearing losses and in some cases impact their mental health (Lu & Davis, 2016). A possible way of addressing noise hazard can be applying the use of sound effects in a virtual environment to investigate the safety decision making of construction workers on construction sites with the use of a mini audio player, computer, and headphones as seen in the study by Lu and Davis (2016). A different study focused on mental fatigue as another OSH condition in the construction industry, as it greatly affects attentional resources and impairs cognitive capacity (Tehrani et al., 2021). The study utilized VR environment and EEG signals for the assessment of mental fatigue of construction workers that are working at heights and discovered that the exposure of construction workers to height caused an increase in the levels of mental fatigue in them (Tehrani et al., 2021).

Huang et al. (2021) designed six virtual scenarios of different types of commonly encountered construction site injuries: electrical injury, injuries caused by object impact, mechanical injury, injuries caused by foundation collapse, injuries caused by confined space, and injuries caused by falling. Some of the virtually simulated scenarios involved trainees inserting damaged plugs into a distribution box so as to cause electrical injury; or trainees getting hit by falling objects such as steel pipes; or trainees walking within the operating radius of a functioning excavator to induce mechanical injury; or trainees working on foundation slabs with cracks as well as deep wells with limited oxygen to induce falls and asphyxiation (Huang et al., 2021). In order to understand the impact of fear on postural stability of ironworkers, Habibnezhad et al. (2019) developed a virtual construction site that exposed ironworkers to extreme height and a structural beam moving toward them while also measuring the heart rate of the participants. It was observed that height had a negative impact on postural stability, while self-judged fear decreased postural instability both in the presence and absence of height (Habibnezhad et al., 2019). In another closely-related study, Hsiao et al. (2005) measured the gait patterns, cardiovascular reactivity, and the walking instability measurements of both experienced and inexperienced construction workers performing tasks on real planks on a virtual scaffolding. It was observed that the novice workers were more unstable as compared to construction workers, and they also had higher mean strides width than the experienced workers, which indicates higher level of falls for the novice workers (Hsiao et al., 2005).

4.2.4. Nature of construction activity and stage at which immersive technologies are applied

Construction hazards occur at different construction activities and stages of asset life cycle and the effectiveness of the mitigating measures implemented could be dependent on the understanding of such activity and stages. Some of the focus areas of construction OSH management studies include road construction (Kim et al., 2021), railway construction (Xu & Zheng, 2021), multi-storey buildings (Lucena & Saffaro, 2020), roofing (Hasanzadeh et al., 2020b), reinforcing bar (Abbas et al., 2020), steel erection (Teizer et al. 2013), and scaffolding (Tehrani et al., 2021). Kim et al. (2021) developed a VR environment for the simulation of road con-

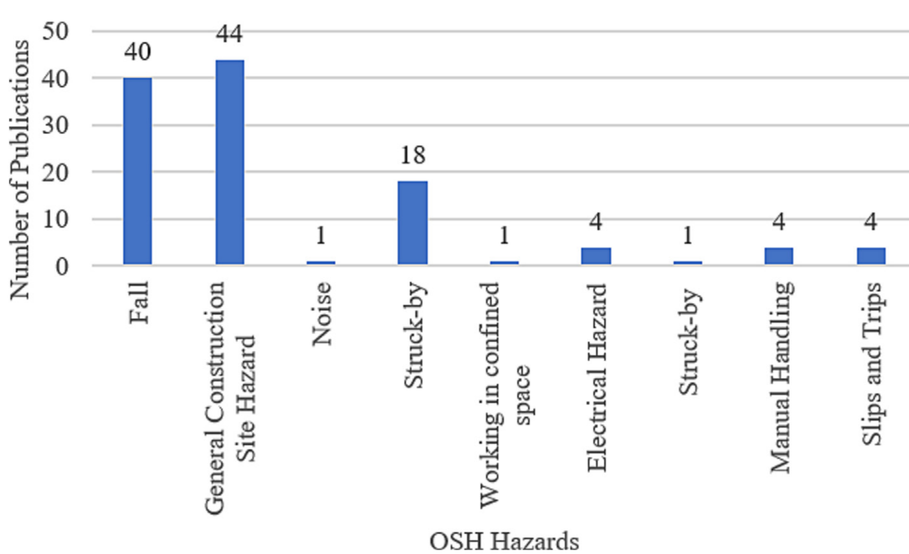

Fig. 10. Distribution of publications with the OSH hazards addressed.

struction works that was used to investigate how repeated exposure to hazards in road construction tasks affects the vigilant behavior of worker operations. Kim et al. (2021) observed a decline in the vigilant behaviors of workers in response to approaching vehicles over time. Xu and Zheng (2021) focused on another area of construction by conducting a pilot study of a railway station under construction that involved several machineries working together for level crossing removal and site rebuild. The developed immersive and interactive multiplayer VR platform through this study was found to be effective in the safety training of workers. A mobile-based VR technology was used for the simulation of two multi-story buildings consisting of six floors in order to present different ways for the exploration of virtual construction sites for hazard identification using low-cost devices (Lucena & Saffaro, 2020). It was observed that one of the exploration methods (which required strict guidelines to workers) was more effective than the other exploration method (which required no guidelines in the hazard identification of workers; Lucena & Saffaro, 2020).

However, the majority of research studies on the application of ImTs for construction OSH management have concentrated on the design (Hadikusumo & Rowlinson, 2002; Shafiq & Afzal, 2020; Afzal & Shafiq, 2021) and the construction phases (Li et al., 2006; Kim et al., 2021), with a few on the demolition phase (Adami et al., 2021) as shown in Fig. 11. This could be because the design phase offers the greatest ability to mitigate adverse OSH outcomes that manifest during the construction phase. It could also be due to the difficulty in the reproduction of demolition scenarios in a virtual environment. The SLR conducted by Farghaly et al. (2021) on BIM and VR harmonization for construction OSH management recognized that designers have ample opportunities to lower risks during construction and maintenance, through the implementation of design for safety principles. The study, however, identified three main challenges regarding the application of VR and AR for design for safety, which are inadequate quality of design models, scalability, and construction sequencing.

4.2.5. Hierarchy of control

Hierarchy of controls (which comprises of elimination, substitution, engineering controls, administrative controls and personal protective equipment (PPE)) have been implemented for OSH management in the construction industry (Nnaji & Karakhan, 2020). For example, it was observed that administrative control was implemented by Comu et al. (2021), who proposed VR safety training of workers on hazard identification in order to prevent injuries and fatalities. Administrative control, which can be defined as the various established policies such as ensuring adequate safety trainings in order to promote safety in a work environment (Environmental Health and Safety, 2017), was also implemented by Kim et al. (2021). Kim et al. (2021) examined the efficacy of VR technology for the mitigation of a decline in the level of risk perception of construction workers. In another study that tried to eliminate hazards, VR tools were used by designers and builders to decide on alternative designs and construction scenarios (Sacks et al., 2015). Fig. 12 shows the distribution of articles based on the hierarchy of control.

4.2.6. Complementary industry 4.0 technologies for construction OSH management

Other industry 4.0 technologies used to complement ImTs for construction OSH management are robots (Adami et al., 2021), big data and analytics (Lee et al., 2020), sensors (Huang et al., 2021), and BIM (Khan et al., 2021). The simulation of a virtual environment for the authentic learning of construction safety and health was proposed for undergraduate students and practitioners with random forest, a machine learning technique used for the analysis of the feedbacks from the undergraduates and practitioners (Lee et al., 2020). It was then discovered that the authentic learning characteristics can be grouped into three (authenticity, group work, and guidance) with these three factors being more important than the role (student or practitioner) (Lee et al., 2020).

Khan et al. (2021) conducted a review on the integration of VR, AR, and MR with BIM in the construction industry for various domains including construction health and safety, construction monitoring, and training and education with health and safety reaping benefits from these ImTs. Construction workers with the use of VR-based training experienced different strategies of demolishing a concrete block with a robot to determine which of the strategies was safer and more effective (Adami et al., 2021). To address the issue of restricted field of view and the non-negligible weight of augmented reality devices such as HMDs, heavy helmets or goggles, a mobile projective AR (MPAR) system (which consists of a portable projector, a camera and a laptop) is mounted on mobile collaborative robots and is used to project virtual information on planar or three dimensional (3D) physical surfaces (Xiang et al., 2021). The MPAR also promotes human-robot collaboration on construction sites (Xiang et al., 2021).

4.3. Challenges involved in application of immersive technologies for construction occupational safety Health management

Although, ImTs have the potential to revolutionize OSH management within the construction industry, especially owing to their ability to transfer knowledge without necessarily exposing participants to real-life operational hazards, some challenges associated with ImTs have been raised by different studies, of which the most prominent ones will be discussed here.

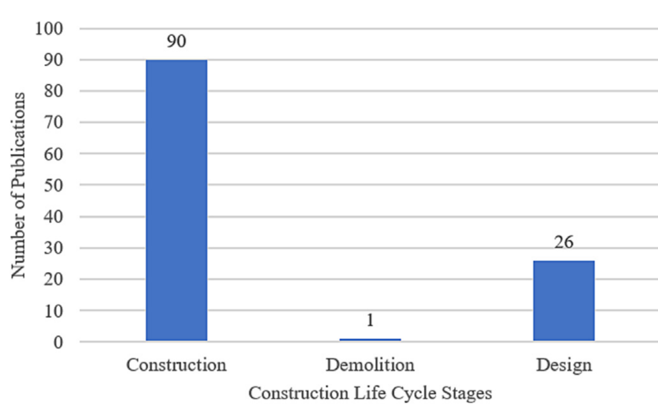

Fig. 11. Distribution of publications with the construction life cycle stages.

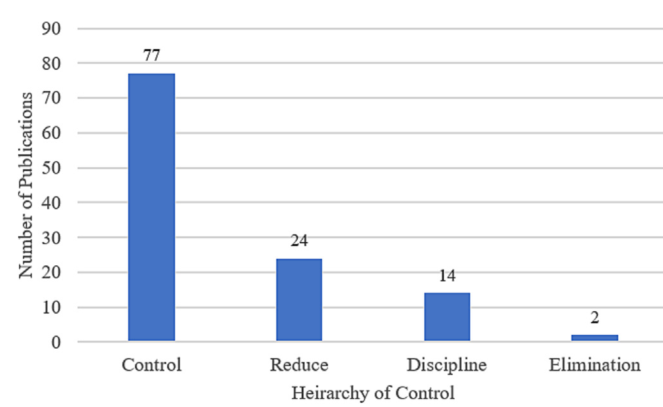

Fig. 12. Distribution of publications with the hierarchy of control.

One of the challenges associated with ImTs for construction OSH management include simulation sickness experienced by users of these technologies, especially within virtual environments. For example, some of the construction professionals that participated in a study by Bhagwat et al. (2021) complained of dizziness, headache, eye stress, and discomfort, especially for those that wore spectacles while using a head-mounted display. This was also validated by Joshi et al. (2021) when they reported that a small fraction of the respondents that participated in their VR-based experiments complained of some minute symptoms of simulation sicknesses. Han et al. (2021) further buttressed these findings when they stated that not all the participants of their VR experiments felt comfortable wearing the devices associated with virtual tasks.

Another challenge with the application of ImTs for construction OSH management is the level of restrictions in the navigation of users of a virtual environment. Participants of a VR training could not generate exact replica movements like they would in real life, which sometimes creates an adverse effect on the level of realism of the immersive experience (Xu & Zheng, 2021), and may in turn lead to participants undermining the seriousness of the knowledge acquired. In a different but related study, users of a virtual safety assessment system also complained of the complexity of navigation within the system (Li et al., 2012b). Although, Xu and Zheng (2021) proposed the use of a 360-degree walking pad, which can also be referred to as a treadmill, for the actual movement of workers, it is, however, expensive to purchase and setup for use to aid movement of participants in a virtual environment. Users of a virtual environment complained of difficulty in navigating through the environment due to abundant rendering and animation, which made the users confused and distracted (Xu & Zheng, 2021). Similarly, the discrepancy in the movement of users of ImTs and the virtual animations had an adverse effect on the sense of presence in a virtual environment (Shi et al., 2019). Users of virtual environments related to working at height were prone to overestimating the actual altitude of a real, physical height as participants were observed adjusting their stride lengths at a simulated height when compared to ground level (Hsiao et al., 2005).

Another challenge associated with the use of ImTs is effectiveness of communication, as seen in the VR-based system for construction safety training and education developed by Seo et al. (2021). The system was a one-man system, thereby making it difficult for field officials to interact with one another, so communications with co-workers, safety managers, and field managers using radio were not considered. It was also difficult to conduct safety training for a large number of construction workers as the motion sensor used to detect movement of people within the environment could only detect two people (Seo et al., 2021).

The cost and duration of the implementation of ImTs for construction OSH management is another prominent limitation for ImTs, especially as Eiris et al. (2020) observed that the total replication of hazards in a virtual construction site was impracticable as it required high computational costs and long development times to assemble observable hazard scenarios in a virtual construction site. Also, Afzal and Shafiq (2021) asserted that the development of a virtual environment for a new construction project can be time-consuming, while educators raised concerns regarding the feasibility of implementing a virtual safety education system due to financial costs of the development of a virtual safety education system (Pedro et al., 2016). The cost and development time limitation could be due to what Abbas et al. (2020) realized about construction projects with regard to their uniqueness and complexity, which makes it challenging to replicate construction site experience in a virtual environment. In addition, the difficulty in simulating a real construction site could also lead to a lesser sense of presence and feeling of realism in a virtual construction site, which could have a huge adverse effect on the OSH performance of construction workers and students using the developed virtual construction site. The real world construction sites are complex with unpredictable hazard situations (Shi et al., 2019), and therefore there could be latent hazard conditions yet to be addressed in academic studies with the application of ImTs. Furthermore, there is a lack of manpower needed for the development and implementation of ImTs, as according to Ahmed (2019), there is lack of expertise and technicians for the development, implementation, and maintenance of ImTs.

Inconsistency in the level of detail for an entire simulation of a virtual environment is another challenge in the use of ImTs, as it has adverse effects on the review of the entire building by safety experts and project manager as some critical areas of safety planning may be unintentionally ignored for components with lower level of details (Afzal & Shafiq, 2021). The MPAR system designed by Xiang et al. (2021) to address the discomfort experienced by users of augmented reality devices experienced challenges of image brightness caused by other light sources such as sunlight, which resulted in less visible virtual information projected onto planar or 3D surfaces. Finally, tutors are worried that the mobile devices used in the implementation of mobile-based VR and AR framework proposed by Le et al. (2015) can be a distraction to construction safety students in the classrooms.

5. Conclusions

This study conducted a comprehensive systematic review on the applications of ImTs for the effective OSH management in the construction industry. This study also presented the results of the bibliometric analysis on the broad body of literature on the applications of ImTs for construction OSH management. It has been observed that various research has been conducted on the applications of ImTs for the identification of hazards, training and education, design for safety, risk perception and assessment, and general safety. These studies were conducted with the aim of addressing various types of hazards including working at height, lifting of heavy loads, electrical hazards, and caught in-between objects to avoid injuries and fatalities. The applications of ImTs for construction OSH management has been observed from the literature body to have a huge positive impact on the management of OSH in the construction industry. It has, however, been discovered that there has been a low level of transition from research to industry practice.

Some studies (e.g., Sacks et al., 2013; Afzal & Shafiq, 2021; Han et al., 2021) adopted the use of questionnaires to obtain data from the experimental study to measure the effectiveness of the application of ImTs for addressing construction OSH areas, while different statistical techniques were used to determine how effective ImTs are in the improvement of construction OSH management. Alternative tools used for the collection of data are EEG sensor (Noghabaei et al., 2021; Tehrani et al., 2021), eye-tracking sensors embedded in the head-mounted display (Kim et al., 2021), electrodermal activity (EDA) sensor (Kim et al., 2021), and sphygmomanometer (Huang et al., 2021).

Various studies concluded that ImTs have great potential in the improvements of construction OSH management. Other industry 4.0 technologies such as robotics and big data and analytics can be used to complement ImTs to address the poor OSH statistics in the construction industry. It is therefore highly recommended that construction companies seek to make use of ImTs for the OSH management at the different stages of construction, which include the design stage, construction stage, maintenance stage, and demolition stage. Compared to other SLRs on the application of ImTs on construction OSH management, this review focused widely on the application of ImTs, which includes VR, AR, and MR in addressing construction OSH areas, different types of construction OSH hazards, and different types of construction OSH conditions. The above findings can therefore be used to encourage the use of ImTs in the industry to improve the poor OSH situation in the construction industry.

5.1. Study limitations

Some of the papers obtained for SLR in this study may have been left out due to the definition of inclusion and exclusion criteria, which focused mainly on journal articles within Scopus, WoS, and EV databases and written in English language only. The study did not consider other search engines. However, the articles obtained in this study encompass the main body of knowledge in the scope of this study. Nonetheless, future studies could include other databases and other document types.

5.2. Main gaps in existing body of knowledge

Some limitations to the studies conducted on the applications of ImTs for construction OSH management were observed. A common limitation observed in various studies was the sample size, as studies were conducted with relatively small sample size (Lu & Davis, 2016; Din & Gibson, 2019; Hasanzadeh et al., 2020). Many experienced construction workers who are trained to identify hazards are prone to underestimate the gravity of the repercussions of the identified hazards and therefore engage in risky behaviors (Jeon & Cai, 2021).

Users of a virtual construction simulator for investigating the effects of construction sounds on worker decisions were exposed to a short time exposure to construction sounds, with a maximum of 1 hour of sound exposure (Lu & Davis, 2016). The users also attempted to remove the headphones used to simulate construction sounds as the sounds irritated the user (Lu & Davis, 2016). Diego-Mas et al. (2020) discovered that when participants received safety training with the use of virtual reality technology, little training was transferred to jobsites three months after the VR-based training session as the mode of training did not increase the risk perception of workers (Jeon & Cai, 2021). The readiness of tertiary institutions to incorporate safety learning with the use of ImTs in the current syllabus will play a crucial role in construction safety training for students (Le et al., 2015). There is therefore a need to proffer solutions to the numerous challenges in the use of ImTs, such as simulation sickness or huge financial costs. Not every worker requires learning about every hazard (Afzal et al., 2021) and this could result in developing different ImTs-based construction safety training and assessment for different workers, which could be time consuming and expensive.

5.3. Future Research Considerations for ImTs in construction OSH management

- The different measures used in the assessment of the performance of ImTs include simulation sickness, user experience, and system usability, which are predominantly measured via questionnaires (Joshi et al., 2021). The questionnaires are often furnished with simulation sickness scores to ascertain the suitability and safety of a particular immersive technological platform for conducting research studies. There are also presence questionnaires for the evaluation of user experience and system usability scale questionnaire to determine the expectations of users through a system usability score (Joshi et al., 2021). Future research should work on the development of alternative tools for the assessment of the performance of ImTs, which could apply other complementary industry 4.0 technologies such as internet of things (IoT) and big data and analytics and compare the effectiveness of the use of these developed tools' performance assessment with that of the use of questionnaires.
- Although the popularity of studies based on ImTs for construction OSH management is gradually increasing, there are still several construction trades that are yet to be explored, especially glazier, plumbing, carpentry, and welding. These under-represented construction trades occur at high frequencies and volumes on almost every construction site, which in turn heightens their risk priority numbers. They also have inherent hazards that must be addressed for the overall improvement of OSH performance within the trade and in the construction industry. It is therefore imperative that research should be conducted on the applications of ImTs for construction OSH management in these various construction trades.
- Further work should be done to investigate the reason behind a portion of participants experiencing simulation sickness during the use of virtual environment, while another portion of participants do not feel any symptoms of simulation sickness and possibly proffer ways for the reduction or elimination of simulation sickness. It is recommended that larger sample sizes are used to increase the effect of the study and the development of a possible solution to simulation sickness, especially as the sample sizes have also been a common limitation observed in literature.
- There is limited research in the application of ImTs for health-related conditions such as musculoskeletal disorders, which could be caused by the continuous execution of strenuous activities, skin conditions such as contact dermatitis, and skin cancer which could be caused by exposure to harmful substances such as dampened cement or tars or exposure to or sunlight. Further research should be conducted on how VR, AR, and MR can be applied for identification of health hazards, health training, and the risk assessment and control of hazardous substances on construction sites. Further work should also be conducted to determine the level of retention of participants of OSH training with the use of ImTs and to determine the intervals of training to achieve the optimum impact on the level of understanding of the construction OSH trainees and the level of retention of the trainees.
- The OSH training should focus on different construction trades such as the electrical construction trade, glazier, carpentry, masonry, and many more.
- Studies should be conducted on the effects of collaboration amongst construction workers undertaking a task in a virtual environment by developing a platform that enables the interactive control of the ImT system by several construction workers and to switch between viewpoints. This is to ensure a more effective assessment of the risk-taking behaviors of construction workers.
- The accuracy of the calibration of the movement of construction workers and students and the animation in a virtual environment should be improved with further research on more suitable technologies to improve the accuracy of calibration.
- The number of countries around the world that have contributed to the study on applications of ImTs for construction OSH management are few in comparison to the total number of countries worldwide. This finding indicates that the applications of ImTs for construction OSH management are slow-paced globally and are only in the nascent phase. This means that further research studies should be made to promote the applications of ImTs for construction OSH management globally, especially in countries lacking in studies in this area.
- The low visibility issue with the MPAR should be studied to determine possible solutions to the interference by external sources of light such as studies on the application of laser pro-

jectors, as it has been noted from literature that MPAR is one of the possible solutions to the health and safety issues inherent with the use of ImTs.

- There is an urgent need to intervene in the low adoption of the research studies on the application of ImTs for construction OSH management by the industry. It is therefore recommended that studies are conducted to determine possible reasons for the low transition level of study to industry practice of ImTs and proffer possible solutions to these reasons. In addition, the developed ImTs in various studies should be further evaluated and validated sufficiently for industrial application with the use of a larger sample size of construction practitioners, as this could be a factor in making the industry more interested in the adoption of ImTs for construction OSH management. Furthermore, some studies were conducted on students (Lu & Davis, 2016; Jeon & Cai, 2021; Kim et al., 2021; Noghabaei et al., 2021) and to further validate the developed ImTs for construction OSH management, further works should be conducted on these studies by evaluating the performance of the developed ImTs on construction practitioners.
- The financial analysis of the use of ImTs in comparison to traditional methods for the management of different areas of OSH in the construction industry should be conducted to further understand the overall benefits and limitations of using ImTs for construction safety management.
- Finally, to further understand the relationship between the different feelings of construction workers caused by construction sounds and their safety decisions in the virtual environment, further studies should be conducted using different combinations of construction sounds ranging from intermittent sounds, low frequency sounds, to continuous and impulsive sounds.
- From the results of this review, it has been observed that there has been a disproportionate focus on the applications of ImTs of construction occupational safety management as opposed to construction occupational health management. Occupational health management is, however, very critical in the construction industry as there are many occupational health hazards inherent in the industry. It is anticipated that the use of ImTs for occupational health management would further enhance OSH management in the construction industry. This SLR therefore proposes that future studies should be conducted to investigate how ImTs can be used in addressing occupational health hazards and also compare the performance of ImTs with that of the conventional methods of occupational health management. In addition, training has been observed to be an effective method for addressing poor OSH performances. Consequentially, this article puts forward as a proposition that ImTs for occupational health training would be more effective than the conventional methods of training in the construction industry. This, however, requires testing. It is therefore recommended that further studies should be conducted to compare the effectiveness of ImTs for occupational health training to that of the conventional methods of training.

Declarations of conflict of interest

The authors declare no conflict of interest.

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A systematic review of the evidence for effectiveness of interventions to address transport and other unintentional injuries among adolescents

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ABSTRACT

Introduction: Globally, injuries are a leading cause of mortality and morbidity for adolescents, which disproportionately affect the disadvantaged. To build an investment case for adolescent injury prevention, evidence is needed as to effective interventions. *Methods:* A systematic review of peer-reviewed original research published between 2010–2022 was conducted. CINAHL, Cochrane Central, Embase, Medline and PsycINFO databases were searched for studies reporting the effectiveness of unintentional injury prevention interventions for adolescents (10–24 years), with assessment of study quality and equity (e.g., age, gender, ethnicity, socio-economic status). *Results:* Sixty-two studies were included; 59 (95.2%) from high-income countries (HIC). Thirty-eight studies (61.3%) reported no aspect of equity. Thirty-six studies (58.1%) reported prevention of sports injuries (commonly neuromuscular training often focused on soccer-related injuries, rule changes and protective equipment). Twenty-one studies (33.9%) reported prevention of road traffic injury, with legislative approaches, commonly graduated driver licensing schemes, found to be effective in reducing fatal and nonfatal road traffic injury. Seven studies reported interventions for other unintentional injuries (e.g., falls). *Discussion:* Interventions were strongly biased towards HIC, which does not reflect the global distribution of adolescent injury burden. Low consideration of equity in included studies indicates current evidence largely excludes adolescent populations at increased risk of injury. A large proportion of studies evaluated interventions to prevent sports injury, a prevalent yet low severity injury mechanism. Findings highlight the importance of education and enforcement alongside legislative approaches for preventing adolescent transport injuries. Despite drowning being a leading cause of injury-related harm among adolescents, no interventions were identified. *Conclusion:* This review provides evidence to support investment in effective adolescent injury prevention interventions. Further evidence of effectiveness is needed, especially for low- and middle-income countries, populations at increased risk of injury who would benefit from greater consideration of equity and for high lethality injury mechanisms like drowning.

1. Introduction

Globally, injuries are the leading cause of death in adolescents aged 10–24 years, claiming more lives than communicable or non-communicable diseases (Ward et al., 2021). In 2019, two-fifths (40.9%) of all deaths among adolescents were due to injuries, whether intentional or unintentional (Ward et al., 2021). Transport and unintentional injuries accounted for over half of this burden (24.8%). Injuries also cause significant health-related disability, which can have lifelong impacts (McGee, Sethi, Peden, & Habibula, 2004). Despite this, injury among adolescents has

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received far less policy and programmatic focus than injury-related harms in young children and adults (Rivara, 2012; Patton et al., 2012).

Recent data from the Global Burden of Disease Study 2019 indicate that over the past 30 years, the proportion of all-cause deaths and disability adjusted life years (DALYs) from transport and other unintentional injuries in adolescents has remained largely unchanged (Peden et al., 2022). Furthermore, earlier gains in reducing adolescent transport and other unintentional injury have stalled in high-income countries, while fatal and nonfatal injury represent a growing burden in low- and middle-income countries (Ward et al., 2021; Peden et al., 2022).

Within individual countries, there is a clear socioeconomic gradient evident in injury-related harms; people who are more socioeconomically disadvantaged have a higher rate of injury and poorer outcomes (Haagsma et al., 2020; Williams et al., 1997). Socioeconomic factors such as lower neighborhood and family income, unemployment, geographical remoteness, and low parental education (Remes et al., 2019; Yuma-Guerrero et al., 2018; Goldman et al., 2018; Peden and Franklin, 2021) have all been found to be positively correlated with increased injury-related mortality and morbidity for adolescents. There is also a greater burden of injury in low- and middle-income countries and among First Nations populations in high-income countries (Vecino-Ortiz et al., 2018; Sleet, 2018). Equity is therefore appreciated as an important consideration when developing, implementing, and evaluating injury prevention interventions (Ryder et al., 2020).

To reduce and prevent transport and other unintentional injury-related harms for adolescents, investment is vital. However, to be most effective, investment should target evidence informed preventive interventions. Of concern, previous research suggests there is limited evidence of effective interventions for adolescents (Salam et al., 2016). The primary aim of this systematic review was to identify and report the evidence for the effectiveness of interventions to address transport and other unintentional injuries among adolescents aged 10–24 years worldwide. A secondary aim, given the socio-economic gradient for injury (Haagsma et al., 2020), was to assess the evidence with respect to considerations of equity.

2. Methods

A full systematic review (without meta-analysis) of the peer-reviewed literature was conducted in accordance with the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) statement (LA Moher, Tetzlaff, & Altman, 2009) to identify studies reporting interventions addressing unintentional injury among adolescents. The protocol for this review was prospectively registered with PROSPERO (#CRD42020218967).

2.1. Search strategy and eligibility criteria

Searches for peer-reviewed literature published in English between 1st January 2010 and 31st March 2022 were conducted across CINAHL, Cochrane Central, Embase, Medline (ePub), Medline (Ovid) and PsycINFO databases. Search strategies involved a mix of subject headings and keywords to identify literature reporting the population of interest, relevant injury mechanisms, the intervention and the outcome of interest (Table 1). Search terms varied across databases on the advice of research librarians after detailed consultations and to also match database requirements. The full search strategy can be found in Table S1.

Studies eligible for inclusion were peer-reviewed original research (i.e., excluding literature reviews and meta-analyses) with an exclusive focus on, or separate reporting of data for the prevention of transport or unintentional injury in adolescents aged 10–24 years old (inclusive) in the community (i.e., not clinical or incarcerated populations). The age range of 10–24 years was chosen to reflect adolescent growth and popular understandings of this life phase (Sawyer, Azzopardi, Wickremarathne, & Patton, 2018), as well as the significant, yet neglected injury burden among this age group. Studies were also included if the mean age of participants fell within this age range (i.e., <25 years). Intentional and self-inflicted injuries were excluded. All transport and unintentional injuries were included aside from: self-reported injuries (i.e., injuries reported by the adolescent themselves, as opposed to a health professional, in order to indicate some measure of severity [i.e., clinical diagnosis or medical system treatment]); injuries resulting from poisoning from food, medicines and drugs that were ingested intentionally or through medical or surgical intervention; concussion (as a secondary injury due to an initial head injury); and sunburn (due to likely not requiring medical system diagnosis or treatment).

Types of studies to be included were: cluster randomized controlled trials (RCT) and other RCTs; case control or cohort studies; crossover trials; non-randomized trials; case series with pre-post or post-test outcomes; quasi-experimental designs; observational studies; mixed methods studies; and cost-effectiveness/ cost-benefit/ cost-utility studies.

Prevention interventions were included if they targeted adolescents, parents, caregivers, teachers, or coaches. Secondary or tertiary prevention interventions (i.e., interventions aimed at preventing re-injury or improving treatment or quality of life after injury) and interventions that reported on behavioral or attitude change, rather than reported on fatal or nonfatal injuries were excluded. Studies were included if interventions addressed the outcomes of death or nonfatal injury (defined as any interaction with the healthcare system within 12 months of the initial injury and/or one day or more off usual activities such as work, school, or sport). Studies reporting interventions with outcomes related to sport conditioning or improving sport functioning or performance, as opposed to outcomes with respect to injury were excluded. Similarly, studies reporting the enforcement of interventions or the prevention of incidents (i.e., the outcome of interest being car crashes as opposed to crash-related hospitalized injury) were excluded. The full eligibility criteria can be found in Table S2.

Table 1
Example of search terms.

Category	Example terms
Population of interest	children or youth* or adolescent* or "young adult" or "young adults" or "young person" or "young persons" or "young people
Relevant injury mechanisms	(vehicle or car or traffic or transport or cycl* or pedestrian or boat*), (collision* or crash* or accident* or injur*), (falls or "fall injury" or "fall injuries" or drowning or burns or "burn injury" or "burn injuries" or "electric shock" or "heat injury" or "heat injuries" or "cold injury" or "cold injuries" or poisoning)
The intervention	intervention* or countermeasure* or deterrence or preventive or preventative or prevention or program
Outcome of interest	injury or injuries or "physical disability" or hospitali?ation or mortality or fatality or "quality of life" or QOL or well#being

2.2. Literature screening and data extraction

Retrieved citations were exported into Covidence for screening (Veritas Health Innovation, 2021). Independent dual screening of 20% of studies by title and abstract followed by full text screening was undertaken by authors BB and LT. Conflicts were resolved by a third reviewer (AP). Independent data extraction was conducted by both authors (BB, LT), with dual extraction of 20% of included studies (AP, HM, and AW). Reference and citation searches of included papers were conducted, as was reference checking of excluded literature reviews and meta-analyses.

Data extraction was performed using a custom-built Microsoft Excel spreadsheet. Data extracted included study design, study population and sample size, injury mechanism addressed (coded to ICD-10 categories of injury (World Health Organization, 2020), outcome or measures of effect, intervention type, intervention setting and intervention effectiveness (direction/magnitude of effect for each outcome by age, sex and any other relevant variable). Where studies reported intentional and unintentional injuries (i.e., unintentional and intentional firearm injuries) only data related to unintentional injuries were extracted and reported. Income levels of countries represented in included studies were assessed when completing the review using World Bank open data country profiles (The World Bank, 2022).

2.3. Assessment of literature

Included studies were assessed against the Australian National Health and Medical Research Council's (NHMRC) Levels of Evidence (Australian Government National Health and Medical Research Council (NHMRC), 2005). Levels of evidence range from Level I (a systematic review of Level II studies [randomized controlled trials]) to Level IV (case studies with either post-test or pre-test/post-test outcomes) (Australian Government National Health and Medical Research Council (NHMRC), 2005).

The methodological quality of included studies was assessed using the appropriate Johanna Briggs Institute (JBI) critical appraisal checklist based on study type (Aromataris, 2020). This was done independently by two authors (BB and LT) with 20% dual screening (AP, HM, AW). Checklists provide a score based on assessment of a range of study design components. The threshold for inclusion was a combined score of 5 or more. Given the inequitable burden of injuries worldwide (Haagsma et al., 2020), specific attention was paid to issues of equity within the identified studies. Equity was assessed using PROGRESS Plus (i.e., factors such as place of residence, education, socio-economic position, age, disability, sexual orientation among others) and displayed as a modified four-level rating as detailed by Ryder et al (Ryder et al., 2020), ranging from 1-not at all evident (no consideration or discussion of equity) to 4 – highly evident.

3. Results

3.1. Description of study characteristics

A total of 15,374 studies were identified across the database searches. After removal of duplicates (n = 3,909), 11,465 studies were screened for inclusion by title and abstract. Of these, 11,014 studies were deemed irrelevant. A total of 451 full text studies were screened for eligibility. After the removal of 389 studies at full text review, a total of 62 studies were included for data extraction (Fig. 1).

Of the 62 included studies (Achenbach et al., 2018; Åkerlund et al., 2020; Åkerlund et al., 2022; Anderson et al., 2017; Baker et al., 2016; Barboza et al., 2019; Bello et al., 2011; Berecki-Gisolf et al., 2001–2017. 2020,; Bollars et al., 2014; Bonne et al., 2018; Chena et al., 2019; Collard et al., 2010; Conner and Smith, 2017; Cusimano et al., 2011; Edwards et al., 2013; Ehsani et al., 2014; Emery et al., 2022; Emery et al., 2021; Emery et al., 2020; Fell et al., 2011; Fell et al., 2014; Ferdinand et al., 2015; Foss et al., 2018; Gatterer et al., 2012; Grooms et al., 2013; Hägglund et al., 2013; Hasebe et al., 2020; Hassan et al., 2017; Hirschberg and Lye, 2020; Inada et al., 2019; Ji et al., 2017; Kaafarani et al., 2015; Keall et al., 2015; Kiani et al., 2010; Kliethermes et al., 2019; Kosola et al., 2016; Krist et al., 2013; Krutsch et al., 2020; Lacny et al., 2014; Layba et al., 2017; Longo et al., 2012; Males, 2013; Marshall et al., 2016; McGuine et al., 2011; Mendez-Rebolledo et al., 2021; Myers and Lehna, 2017; Nauta et al.,

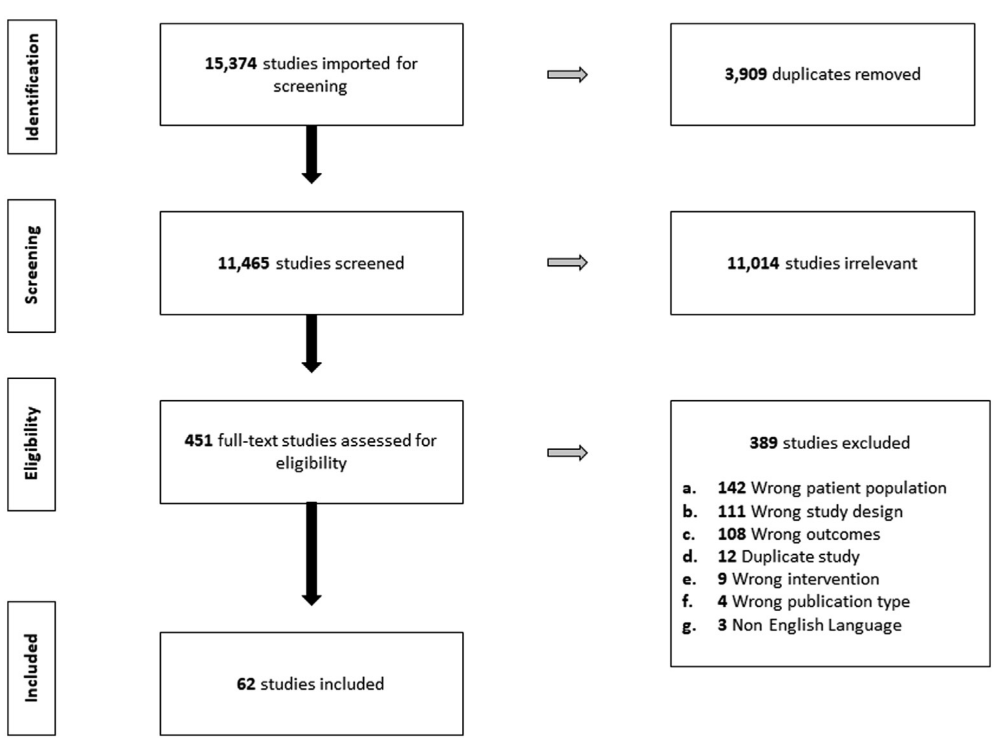

Fig 1. PRISMA flow chart.

2013; Owoeye et al., 2014; Reinold et al., 2018; Richmond et al., 2016; Richmond et al., 2016; Rouse et al., 2013; Scherer et al., 2015; Sherk et al., 2018; Silvers-Granelli et al., 2018; Slauterbeck et al., 2019; Steffen et al., 2013; Tashiro et al., 2016; Toledo et al., 2012; Waldén et al., 2012; Whalan et al., 2019; Zarei et al., 2020), 19 unique countries were represented, most notably the United States (US, n = 23 studies; 37.1% of all studies) followed by Canada (11 studies; 17.7%), and Sweden (n = 5; 8.1%). The bulk (95.2%; n = 59) of studies were from high-income countries. When assessed against NHMRC level of evidence criteria, there were no level I studies (i.e., a systematic review of randomized controlled trials). Nineteen studies were ranked as level II (randomized controlled trials; 30.6% of included studies). A low proportion (n = 5, 7.8%) ranked as level IV (case studies with either post-test or pre-test/post-test outcomes; all from the US and Canada). The full study characteristics of each of the included studies can be found in Table S3.

Sixty percent of all studies (61.3%; n = 38) were rated as having no consideration or discussion of equity. Against the PROGRESS Plus framework, the most commonly reported variables were age (n = 54; 87.1%) and gender (n = 42; 67.7%). The full equity assessment using PROGRESS Plus can be found in Table S4. No studies evaluated injury prevention interventions for First Nations adolescents.

Among the included studies there were 25 (40.3%) RCTs, 15 (24.2%) cohort studies and 11 (17.7%) quasi experimental studies (Table S5). Included studies most commonly described interventions to reduce sports injury (36 studies; 58.1% of included studies), followed by road traffic injuries (21 studies; 33.9%). Three studies (4.8%) evaluated fall prevention interventions and two examined burn prevention (Table 2).

3.2. Sports injury

There were 36 (58.1%) studies that reported interventions to reduce sports injury among adolescents, all from high-income countries. The level of evidence was quite high for sports injury prevention interventions; 47.2% of studies (n = 17) were assessed as evidence level II (Table 3).

The most common sport reported was soccer (football) (50.0%; n = 18) and interventions were most commonly neuromuscular training (generally for warm up), rule modification (commonly body checking [i.e., when a defensive player crashed into an opponent using the hip or shoulder] policies in Ice Hockey), and protective equipment (Table 3).

With respect to neuromuscular training, the most commonly reported interventions were various iterations of the International Federation of Association Football (FIFA) neuromuscular training program (i.e., FIFA 11, FIFA 11+, FIFA 11 + Kids). This program was generally found to be effective for preventing a range of injuries including lower extremity injuries, knee injuries, and training injuries. Effectiveness was enhanced with higher compliance with the program (Hägglund, Atroshi, Wagner, & Waldén, 2013). Neuromuscular training was also found to lower injury risk associated with basketball (Emery et al., 2021; Foss et al., 2018; Longo et al., 2012), field hockey (Barboza et al., 2019), handball

Table 2
Studies evaluating injury prevention interventions by injury mechanism, country, and country World Bank income level as at 2022 (N = 62).

Injury type	Country (Reference)	World Bank Income level	Total number of studies	% of total studies
Burns	Canada (Richmond et al., 2016) US (Myers & Lehna, 2017)	High	2	3.2
Falls	Canada (Sherk et al., 2018) The Netherlands (Nauta et al., 2013) New Zealand (Keall et al., 2015)	High	3	4.8
Firearm-related injuries	US (Tashiro et al., 2016)	High	1	1.6
Road traffic injuries	Australia (Hirschberg & Lye, 2020) Canada (Richmond et al., 2016; Sherk et al., 2018) China (Ji et al., 2017) Finland (Kosola et al., 2016) Israel (Toledo et al., 2012) Japan (Inada, Tomio, Nakahara, & Ichikawa, 2019) UK (Edwards et al., 2013) US (Anderson et al., 2017; Bonne et al., 2018; Conner and Smith, 2017; Ehsani et al., 2014; Hassan et al., 2017; Kaafarani et al., 2015; Layba et al., 2017; Males, 2013; Rouse et al., 2013; Scherer et al., 2015; Fell et al., 2011; Fell et al., 2014; Ferdinand et al., 2015)	High	21	33.9
Sports injuries	Australia (Whalan, Lovell, Steele, & Sampson, 2019) Belgium (Bollars et al., 2014) Canada (Cusimano et al., 2011; Lacny et al., 2014; Marshall et al., 2016; Richmond et al., 2016; Steffen et al., 2013; Emery et al., 2022; Emery et al., 2021; Emery et al., 2020) Chile (Mendez-Rebolledo et al., 2021) Germany (Achenbach et al., 2018; Krutsch et al., 2020) Italy (Gatterer et al., 2012; Longo et al., 2012) Japan (Hasebe et al., 2020) The Netherlands (Barboza et al., 2019; Collard et al., 2010; Krist et al., 2013) Spain (Chena, Rodríguez, Bores, & Ramos-Campo, 2019) Sweden (Åkerlund et al., 2020; Åkerlund et al., 2022; Hägglund et al., 2013; Kiani et al., 2010; Waldén et al., 2012) UK (Longo et al., 2012) US (Baker et al., 2016; Foss et al., 2018; Grooms et al., 2013; Kliethermes et al., 2019; McGuine et al., 2011; Reinold et al., 2018; Silvers-Granelli et al., 2018; Slauterbeck et al., 2019)	High	36	58.1
	Brazil (Bello, Mesiano Maifrino, Gama, & Rodrigues de Souza, 2011)	Upper middle		
	Iran (Zarei et al., 2020)	Lower middle		
	Nigeria (Owoeye, Akinbo, Tella, & Olawale, 2014)			
Unintentional injuries	Australia (Berecki-Gisolf et al., 2001–2017. 2020)	High	1	1.6

Note: Some studies dealt with multiple injury mechanisms. Abbreviations: UK = United Kingdom; US = United States of America.

Table 3
Injury prevention interventions for adolescent sports injury (n = 36).

Sport (reference)	Evidence level	Type of injury	Intervention	Age group (years)	Outcome/Measures of effect	Direction of effect (↓↑-) *= statistical significance	Summary of impact
American football (Baker et al., 2016)	III-3	Shoulder	Shoulder stabilising braces	18–22	Rate of injury	↓*	Lower posterior labral tear injury rates for those who wore shoulder braces RR = 0.46 (95% CI, 0.16–1.30; P = 0.14)
					Time missed (practice or game)	↓*	Less time missed with brace use (8.7 vs 36.60 games and practices missed due to shoulder injury; P = 0.002)
					Tear requiring surgery	-	No significant difference in shoulder labral tears requiring surgery was found for brace use vs no brace use
Baseball (Reinold, Macrina, Fleisig, Aune, & Andrews, 2018)	II	Pitching injury rates	6-week weighted ball training program	13–18	Injury rates	↑	The program resulted in increased injury rate.
Basketball (Emery et al., 2021)	III-I	Ankle and knee injury	SHRed Injuries Basketball Neuromuscular Training	11–18	All-complaint ankle and knee injuries	↓	Protective against all-complaint ankle and knee injuries (IRR = 0.64; 95% CI: 0.51, 0.79)
Basketball (Longo et al., 2012)	II	Basketball-related injury	FIFA 11 + program	I: M age = 13.5 C: Mage = 15.2	Overall injury rates per 1000 athlete exposures	↓*	Intervention group injury rates lower than control group (0.95 vs 2.16; P = 0.0004)
					Training injury rates	↓*	Intervention group injury rates lower than control group (0.14 vs 0.76; P = 0.007)
					Lower extremity injury rates	↓*	Intervention group injury rates lower than control group (0.68 vs 1.4; P = 0.022)
					Acute injury rates	↓*	Intervention group injury rates lower than control group (0.61 vs 1.91; P < 0.001)
					Severe injury rates	↓*	Intervention group injury rates lower than control group (0 vs 0.51; P = 0.004)
Basketball (Foss et al., 2018)	III-I	Basketball-related injury	CORE (trunk and lower extremity exercises) vs SHAM (resistance band running)	5–18 years (M = 14)	Injury rate / 1000 Athlete Exposures (AE)	↓*	Basketball (rate = 4.99 injuries/1000 AE) athletes in the CORE group demonstrated lower injury incidences than basketball (rate = 7.72 injuries/1000 AE; F1,275 = 9.46, P 0.002) athletes in the SHAM group.
Basketball (McGuine et al., 2011)	II	Acute ankle injuries	Lace-up ankle brace	14–18	Injury rates	↓*	The rate of acute ankle injury (per 1000 exposures) was 0.47 in the braced group and 1.41 in the control group (Cox hazard ratio [HR] 0.32; 95% confidence interval [CI] 0.20, 0.52; P < 0.001).
Field Hockey (Barboza et al., 2019)	III-I	Non-contact / Contact: Ball or stick; Ground; Player	Warm up program	M age = 12.1	Injury rate	↓	The injury rate was lower in the intervention group (hazard ratio of 0.64 [95% CI = 0.38, 1.07])
					Time loss injury rate per 1000 player hours	↓	Burden of injuries on players' field hockey participation was lower in the intervention group (difference of 8.42 [95% CI = 4.37, 12.47] days lost per 1000 player-hours of field hockey).
Floorball (Åkerlund, Waldén, Sonesson, & Hägglund, 2020)	III-I	Acute, overuse, lower limb and knee	Injury prevention exercise program	12–17	Injury Incidence	↓	35% lower incidence of injuries in intervention group. Adjusted IRR 0.65, 95% CI 0.52 to 0.81)
					Acute injuries	↓	45% lower incidence of acute injuries (adjusted IRR 0.55, 95% CI 0.37 to 0.83) in intervention group
					Overuse injuries	-	No difference in overuse injuries prevalence (adjusted prevalence rate ratio 0.96, 95% CI 0.73 to 1.26)
Floorball (Åkerlund, Waldén, Sonesson, Lindblom, & Hägglund, 2022)	II	Acute, gradual onset, substantial, and time loss injuries	Injury prevention exercise program	12–17	Total injury incidence	-	No statistically significant differences between groups
					Weekly injury prevalence	↓	35% lower among higher dose group compared to low-dose group
					Weekly prevalence of substantial injury	↓	60% lower among higher dose group compared to low-dose group
Handball (Achenbach et al., 2018)	II	Severe knee injury	Neuromuscular exercise program	<16	Incidence per 1000 hours	↓*	Injury occurred more often in control group (OR: 011 [95% CI: 0.01–0.90]), p = 0.019
		Ankle, lower & upper extremities		<18		-	No significant differences between intervention and control groups
Ice Hockey (Cusimano et al., 2011)	III-I	Hockey-related injuries due to bodychecking	Policy change (lowering bodychecking age)	6–17	Visit to ED due to bodychecking injury	↑	The odds ratio (OR) of a visit to the ED because of a bodychecking-related injury increased after the rule change (OR 1.26, 95% [CI] 1.16–1.38)

(*continued on next page*)

Table 3 (*continued*)

Sport (reference)	Evidence level	Type of injury	Intervention	Age group (years)	Outcome/Measures of effect	Direction of effect (↓↑-) *= statistical significance	Summary of impact
Ice Hockey (Emery et al., 2022)	III-2	Hockey-related injuries	Policy change (disallowing body checking)	15–17	Rate of all injury	↓	Policy prohibiting body checking in non-elite Midget leagues was associated with a 65% lower rate of all injury (IRR = 0.35 (95% CI 0.22 to 0.55))
					Rate of injury with time loss > 7 days	↓	Policy prohibiting body checking in non-elite Midget leagues was associated with a 92% lower rate of injury with time loss > 7 days (IRR = 0.08 (95% CI 0.03 to 0.20))
Ice Hockey (Lacny et al., 2014)	III-2	Hockey-related injuries	Policy change (no body checking)	11–12	Injury incidence	↓	An estimated 1273 injuries would be avoided during just one season with the policy change.
Organised sport (Kliethermes et al., 2019)	III-I	Sport-related injury	Serial sports training risk assessment and counselling	8–17	Injury risk	↓	Controls were nearly twice as likely to be injured during the intervention period after controlling for age, sex, baseline injury and level of specialisation.
Physical activity (Collard, Verhagen, Chinapaw, Knol, & van Mechelen, 2010)	II	Physical activity injury	Injury Prevention Lessons Affecting Youth (iPlay)	10–12 (overall)	Total injury	↓	Small nonsignificant intervention effect on total (HR,0.81; 95% [CI], 0.41–1.59),
					Sports club injury	↓	Small nonsignificant intervention effect on sports club (0.69; 0.28–1.68)
					Leisure time injury	↓	Small nonsignificant intervention effect on leisure time injuries (0.75; 0.36–1.55).
				10–12 (less physically active)	Total injury	↓	Total injury incidence (HR,0.47; 95% CI, 0.21–1.06)
					Sports club injury	↓*	Sports club injury incidence was significantly reduced (HR,0.23; 95% CI, 0.07–0.75)
					Leisure time injury	↓	Leisure time injury incidence (HR, 0.43; 0.16–1.14).
Physical activity (Emery et al., 2020)	II	Sport or recreational activity-related injury	iSPRINT	11–16 (girls)	Medical attention injuries	↓	Protective for girls (IRR = 0.289, 95% CI 0.135 to 0.619)
				11–16 (boys)	Medical attention injuries	-	Not protective for boys (IRR = 0.639, 95% CI 0.266 to 1.532)
Soccer (Bollars et al., 2014)	III-3	Soccer-related injuries	Preventive program	M age = 22	Injury rate	↓	21.1% reduction in injury rate (rate ratio = 0.789; 95% confidence interval, 0.776–0.802)
Soccer (Krutsch et al., 2020)	III-2	Severe knee injuries	Specifically adapted preventive training modules	I: M age = 22.7 C: M age = 21.9	Severe knee injury incidence / 1000 h football exposure	↓*	Intervention group severe knee injury (incidence: 0.38 per 1000 h football exposure; prevalence: 9.8%) compared to control group (incidence: 0.68 per 1000 h football exposure; prevalence: 18.0%; $p < 0.05$)
Soccer (Hasebe et al., 2020)	III-I	Hamstring injury	Nordic Hamstring exercise program	C: M age = 16.3 I: M age = 16.7	Time lost to sport injury rate due to hamstring injury	↓*	Time lost to sport injury rate was 1116.3 / 10,000 competition hours for the control compared to 113.7 for the intervention (RR9.81 (CI: 5.42–17.8) $p < 0.001$))
Soccer (Gatterer, Ruedl, Faulhaber, Regele, & Burtscher, 2012)	III-3	Soccer-related injuries	FIFA 11 program	M age = 22	Injury rates / 1000 match hours	↓	Lower injury rate among 6th league intervention team (11.8 (0.3–3.3) than 6th league control team (14.0 (1.8–26.2)
					Injury rates / 1000 total hours	↓	Lower injury rate among 6th league intervention team (3.3 (0.7–5.9) than 6th league control team (4.3 (1.3–7.3)
Soccer (Chena et al., 2019)	III-I	Soccer-related injuries	Exercise program	16–23	Frequency of injury	↓	63.8% reduction in frequency of injury
					Number of injured players	↓	32.9% reduction in number of injured players
Soccer (Hägglund et al., 2013)	III-2	ACL injuries	Neuromuscular training program	12–17	ACL injury rate (high compliance)	↓	88% reduction in the anterior cruciate ligament (ACL) injury rate (RR 0.12, 95% CI 0.01 to 0.85) among high compliance tertile compared to those in the low compliance tertile.
					ACL injury rate (low compliance)	-	Rate of injury among control group players was not significantly different from those in the low-compliance tertile (RR 0.77, 95% CI 0.27 to 2.21).
Soccer (Kiani, Hellquist, Ahlqvist, Gedeborg, & Byberg, 2010)	III-I	Soccer-related knee injuries	HarmoKnee preventive program	13–19	Knee injury incidence rate	↓	The preventive program was associated with a 77% reduction in knee injury incidence (crude rate ratio, 0.23; 95% confidence interval, 0.04–0.83).
					Non-contact knee injury incidence rate	↓	The noncontact knee injury incidence rate was 90% lower in the intervention group (crude rate ratio, 0.10; 95% confidence interval, 0.00–0.70).

Table 3 (*continued*)

Sport (reference)	Evidence level	Type of injury	Intervention	Age group (years)	Outcome/Measures of effect	Direction of effect (↓↑-) *= statistical significance	Summary of impact
Soccer (Krist, van Beijsterveldt, Backx, & Ardine de Wit, 2013)	II	Soccer-related injuries	10 exercise injury prevention program	18–40 (C:M age = 25.1; I: M age = 24.4)	Injury rates	-	No significant differences in the injury rate were found between the two groups.
Soccer (Grooms, Palmer, Onate, Myer, & Grindstaff, 2013)	III-2	Lower extremity injury	F-MARC 11þ – warm up program	18–25	Lower extremity injury	↓	The intervention season had reductions in the relative risk (RR) of lower extremity injury of 72% (RR = 0.28, 95% confidence interval = 0.09, 0.85).
					Time lost due to lower extremity injury	↓*	The intervention season had reductions in the time lost to lower extremity injury (P = 0.01).
Soccer (Owoeye et al., 2014)	II	Soccer-related injury	FIFA 11+	14–19	Overall rate of injury	↓*	The FIFA 11 + programme significantly reduced the overall rate of injury in the INT group by 41% [RR = 0.59 (95% CI: 0.40 – 0.86; p = 0.006)]
					All lower extremity injuries	↓*	The FIFA 11 + programme significantly reduced all lower extremity injuries by 48% [RR = 0.52 (95% CI: 0.34 – 0.82; p = 0.004)].
Soccer (Silvers-Granelli, Bizzini, Arundale, Mandelbaum, & Snyder-Mackler, 2018)	II	Soccer-related injury	FIFA 11+	18–25	Injury rates for high compliance group compared to low compliance	↓*	The Low Compliance group [mean (M) = 13.25, 95% confidence interval (CI) 9.82–16.68, injury rate (IR) = 10.35 ± 2.21] had a significantly higher injury rate than the High Compliance group (M = 8.33, 95% CI 6.05–10.62, IR = 10.35 ± 2.21), p = 0.02.
Soccer (Slauterbeck et al., 2019)	II	Lower extremity injury	FIFA 11+	14–18	Lower extremity injury rates	↑	There were 196 lower extremity injuries among 1825 athletes in the FIFA 11 + group and 172 injuries among 1786 athletes in the control group (1.59 and 1.47 injuries per 1000 Aes, respectively; P = 0.771).
Soccer (Steffen et al., 2013)	II	Soccer-related injury	FIFA 11+	13–18	High adherence	↓	Injury risk was lower for players who highly adhered to the 11+ (injury rate ratio, IRR = 0.28, 95% CI 0.10 to 0.79).
Soccer (Waldén, Atroshi, Magnusson, Wagner, & Hägglund, 2012)	II	Acute knee injuries	Neuromuscular training	12–17	Anterior cruciate ligament injury rate	↓	A 64% reduction in the rate of anterior cruciate ligament injury was seen in the intervention group (rate ratio 0.36, 95% confidence interval 0.15 to 0.85).
					Severe knee injury rate	-	No significant rate reductions were seen for secondary outcomes.
					Acute knee injury	-	No significant rate reductions were seen for secondary outcomes.
Soccer (Whalan et al., 2019)	III-I	Football-related injuries	FIFA 11+ (comparing standard 11 + to rescheduled part 2 of FIFA 11 +)	Standard: M age = 24.8 Rescheduled M age = 23.8	Days lost due to injury	↓*	Significantly lower days lost to injury among rescheduled group (5815vs4303) p = 0.026
					>28 days lost (severe injury)	↓*	Significantly lower days lost to severe injury among rescheduled group (59vs33) p = 0.012
Soccer (Zarei et al., 2020)	II	Football-related injuries	FIFA 11 + Kids	7–14	Injury burden	↓	Injury burden (lay-off days per 1000 h) was 58% lower in the intervention group compared to the control group (RR 0.42 95%-CI 0.37, 0.48)
					Lower extremity injury	↓	Lower extremity injuries (55% reduction) were reduced in the intervention group compared to the control group.
					Training injury	↓	Training (45% reduction) were reduced in the intervention group compared to the control group.
					Knee injuries	↓	Knee injuries (66% reduction) were reduced in the intervention group compared to the control group.
Soccer (Indoor) (Bello et al., 2011)	III-I	Muscle and ankle joint injuries	Rhythmic stabilisation (RS)technique	18–27	Number of muscle and joint injuries	↓	Lower number of injuries among RS group however non-significant (F = 0.192, p value = 0.096).
Soccer (Indoor) (Marshall, Lopatina, Lacny, & Emery, 2016)	II	Soccer-related injuries	Neuromuscular training	13–18	Total number of injuries	↓	38% reduction in injury risk (rate difference = − 1.27/1000 player hours (95% CI − 0.33 to − 2.2)) compared to a standard warm up.
Sports Injury (Richmond, Kang, Doyle-Baker, Nettel-Aguirre, & Emery, 2016)	II	Sports-related injury risk	Neuromuscular training	11–15	All sports injury	↓	reduced risk of all injury: incidence rate ratio (IRR)all injury = 0.30 (95% CI, 0.19–0.49)
					Lower extremity injury	↓	IRR lower extremity injury = 0.31 (95% CI, 0.19–0.51)
					Ankle sprain injury	↓	IRR ankle sprain injury = 0.27 (95% CI, 0.15–0.50)
					Knee sprain injury	↓	IRR knee sprain injury = 0.36 (95% CI, 0.13–0.98)

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Table 3 (*continued*)

Sport (reference)	Evidence level	Type of injury	Intervention	Age group (years)	Outcome/Measures of effect	Direction of effect (↓↑-) *= statistical significance	Summary of impact
Track and Field (Mendez-Rebolledo et al., 2021)	II	Sports-related lower limb injury	Neuromuscular training	11–18	Injury incidence rate	↓	The injury incidence rate was 17.89 (95% confidence interval [CI], 10.24 to 25.54) injuries per 1000 hours of athlete-exposure after CONV training. In contrast, the injury incidence rate was 6.58 (95% CI, 2.02 to 11.15) injuries per 1000 hours of athlete-exposure after NM training.
Volleyball (Foss et al., 2018)	III-I	Volleyball-related injuries	CORE (trunk and lower extremity exercises) vs SHAM (resistance band running)	5–18 years (M = 14)	Injury rate / 1000 Aes	↓*	Volleyball (rate = 5.74 injuries/1000 Aes) athletes in the CORE group demonstrated lower injury incidences than volleyball (rate = 11.63 injuries/ 1000 Aes; $F_{1,149}$ = 11.36, P = 0.001,) athletes in the SHAM group.

Abbreviations: CI: Confidence Interval; ED = Emergency Department; HR = Hazard Ratio; IRR = Incidence Rate Ratio; M = Mean; OR = Odds Ratio; RR = Relative Risk; RS = Rhythmic Stabilisation; *=statistically significant ($p < 0.05$).↓ = reduced injury; ↑=increased injury;- = no change; I = Intervention; C = Control.

(Achenbach et al., 2018), track and field (Mendez-Rebolledo et al., 2021), and volleyball (Foss, Thomas, Khoury, Myer, & Hewett, 2018) (Table 3).

Rule changes were commonly related to either increasing or reducing injury risk as a result of body checking in youth ice hockey. An analytical cross-sectional study (evidence level III-I) found increased odds (OR 1.26; 95% confidence interval [CI] 1.16–1.38) of an emergency department visit due to a body checking injury among younger adolescents when the age for allowing the practice was lowered (Cusimano et al., 2011).

Conversely, an RCT (evidence level III-2) found disallowing body checking in youth leagues was estimated to reduce injury risk for 11–12-year-olds (an estimated 1,273 injuries would be avoided during just one season with the policy change) (Lacny et al., 2014). Additionally, a cohort study (evidence level III-2) found disallowing body checking resulted in a lower rate of all injury (65% lower rate of all injury (Incident rate ratio [IRR] = 0.35 [95% CI 0.22 to 0.55]) and rate of injury with time loss > 7 days (92% lower rate (IRR = 0.08 [95% CI 0.03 to 0.20]) for 15–17-year-olds (Emery et al., 2022) (Table 3).

With respect to equipment and sports injury risk, a cohort study (evidence level III-3) identified shoulder stabilizing brace wear resulted in significantly reduced lower posterior labral tear injury rates (relative risk [RR] = 0.46; 95% CI 0.16–1.30; p = 0.14) and in less practice or game time missed for those using a brace (8.7 vs 36.60 games and practices missed due to shoulder injury; p = 0.002) among 18–22 year old American football players (Baker, Tjong, Dunne, Lindley, & Terry, 2016). An RCT (evidence level II) found lace-up ankle braces significantly reduced the rate of acute ankle injury in basketball for 14–18 year-olds, with a rate of 0.47 in the braced group compared with 1.41 in the control group (Cox hazard ratio [HR] 0.32; 95% CI 0.20–0.52; p < 0.001) (McGuine, Brooks, & Hetzel, 2011) (Table 3).

3.3. Road traffic injury

Of the 21 studies (33.9% of all included studies) reporting interventions to reduce road traffic injury among adolescents, all were from high income countries. Sixteen studies (76.2%) were aimed at preventing driver-related motor vehicle crashes. Among these, legislative approaches were the most common injury prevention intervention, documented in 16 (76.2%) studies. Graduated driver licensing (GDL) schemes were the most common legislative approaches, reported in eight of the studies examining motor-vehicle crashes in Australia (Hirschberg & Lye, 2020), the US (Bonne et al., 2018; Conner and Smith, 2017; Fell et al., 2011; Kaafarani et al., 2015; Males, 2013; Rouse et al., 2013) and Israel (Toledo, Lotan, Taubman-Ben-Ari, & Grimberg, 2012).

Evidence indicates GDL schemes appear to be effective in preventing motor-vehicle-related injuries and fatalities for adolescents. A cohort study (evidence level III-2) found rates of fatal motor-vehicle crashes were significantly lower for 16–17 year-olds (from 14.0 to 8.6 per 100,000 people, p = 0.006) and 18–20 year-olds (from 21.2 to 13.7 per 100,000 people, p < 0.001) after the adoption of GDL schemes 54. A cohort study (evidence level III-2) found injury crash rates of GDL participants are lower compared to non-participants by 12.7% (p < 0.05) (Toledo et al., 2012). Another study (quasi experimental study; evidence level III-2) found a 59% reduction (p < 0.001) in rates of fatal crashes in 14–18 year-olds after the introduction of GDL, with the effect greatest among 16 year-old drivers (−22%; p < 0.001) (Rouse et al., 2013). Significantly lower motor-vehicle crash related injury rates were seen among 16–20 year-old occupants (16–17 year-olds: RR = 0.94; 95% CI 0.88–0.99; 18–20 year-olds: RR = 0.75; 95% CI 0.64–0.88) after the introduction of GDL schemes, however the evidence level of this analytical cross-sectional study was lower (IV) (Conner & Smith, 2017).

Conversely, a cohort study (evidence level III-2) identified that California's GDL scheme resulted in a 7% net increase in traffic fatalities (approximately 60 more fatal crashes and fatalities per year) for 16–25 year-olds compared to the control group not exposed to GDL (Males, 2013) (Table 4).

A range of legislative approaches were found to be ineffective at preventing injury. An analytical cross-sectional study (evidence level IV) reporting the impact of text-messaging restrictions in the US (Michigan) did not identify significant changes in fatal and disabling injury crash rates for 16, 17, and 18 year-olds, nor non-disabling injury crash rates for 18 and 19 year-olds (Ehsani, Bingham, Ionides, & Childers, 2014). In fact, the study found the introduction of legislation increased fatal and disabling injury crash rates for 19 year-olds and 20–24 year-olds, as well as non-disabling injury crash rates for 16, 17, and 20–24 year-olds (Ehsani et al., 2014).

Similarly, a Canadian analytical cross-sectional study (evidence level IV) (Richmond et al., 2016) reported a 408% increase in motor-vehicle collision-related mortality rates for 15–19-year-olds between 1950 and 1970, despite the implementation of legislation criminalizing drinking and driving and requiring seat belts in all new vehicles. However, significant reductions were seen in the next decade with the introduction of additional legislation targeting mandatory seat belt laws and tougher penalties for impaired drivers (Table 4).

The value of combining legislation change with education was underscored by a quasi-experimental study (evidence level II-3) from New Jersey in the United States (Bonne, Suber, Anderson, & Livingston, 2018), which found no initial impact on teenage driver death upon introduction of GDL; however when the GDL scheme was combined with comprehensive education, a significant reduction in adolescent driver deaths (42 vs 22, $p < 0.05$) and adolescent passenger deaths in vehicles operated by another adolescent (19 vs 11 $p < 0.05$) were found. Education-based interventions were also evaluated and found to be effective in significantly reducing the incidence of nonfatal bicycle injuries for 12–13 year-olds (intervention group [χ 2 = 8.137, $p = 0.004$] (Ji, Ye, Lu, Li, & Gao, 2017), annual incidence of moped and scooter injuries (0.8% in 2011 to 0.3% in 2013 [$p < 0.001$]), and estimated incidence of injuries per new moped/scooter license (from 1.8% in 2011 to 1.0% in 2013 [$p = 0.001$]) for 15–16 year-olds (Kosola, Salminen, & Kallio, 2016) and the number of motor-vehicle crash-related injuries treated at a level 1 trauma center for 16–21 year-olds (-37% [$p < 0.05$]) (Layba, Griffin, Jupiter, Mathers, & Mileski, 2017) (Table 4).

3.4. Other unintentional injuries

Seven studies reported the impact of interventions to prevent non-sport and non-road traffic injuries for adolescents. An RCT (evidence level II) found school-based education programs to be effective in reducing the fall injury rates for 7–12-year-olds in the Netherlands (injury incidence density [IID] of 0.14 fall-related injuries per 1,000 hours of physical activity [95% CI 0.09 to 0.18], compared to 0.26 [95% CI: 0.21 to 0.32] for control) (Nauta et al., 2013). While another RCT (evidence level II) found home modifications reduced the rate of falls requiring medical treatment among 10–19-year-olds in New Zealand (0.007 mean annual injury rate [intervention] and 0.028 [control]) (Keall et al., 2015).

An analytical cross-sectional study (evidence level IV) exploring raising minimum alcohol prices in Canada found this approach had no effect on emergency department visits due to an alcohol-related fall injury (Sherk, Stockwell, & Callaghan, 2018). A cohort study (evidence level III-2) on community coalition training in Australia that aimed to increase evidence-based practices that reduce youth injury risk factors (Berecki-Gisolf, Rowland, Reavley, Minuzzo, & Toumbourou, 2001–2017. 2020) was found to result in significant reductions in unintentional and transport injury, as well as unintentional injury-related hospital admissions for 10–14 and 15–19-year-olds when compared to 20–24-year-olds (Table 5).

In the United States, a case series (evidence level IV) found relaxing of legislation around age restrictions for purchasing fireworks was found to have higher burn injury for < 21-year-olds (Myers & Lehna, 2017). Also in the United States, a cohort study (evidence level III-3) found states with more lenient gun control laws had greater firearm-related hospital admissions and in-hospital mortality for < 20-year-olds (Tashiro, Lane, Blass, Perez, & Sola, 2016). Limited change was seen in burn injuries for adolescents aged 10–14-years in an analytical cross-sectional study (evidence level IV) in Canada after the implementation of legislation regarding flammability requirements for children's sleepwear and bedding, and regulations and labeling requirements for child resistant lighters (Richmond et al., 2016) (Table 5).

4. Discussion

Over the past 30 years, the proportion of global deaths and DALYs in adolescents due to injury has barely changed, which arguably reflects failure to sufficiently invest in interventions to reduce injury risk (Peden et al., 2022). To build an investment case for the prevention of adolescent injury-related harm, it is vital to examine the evidence around interventions aimed at preventing injury for this at-risk age group. Cost-effectiveness will be maximized when investment is made in those interventions that are known to be effective. Therefore, this study systematically reviewed the literature reporting interventions for the prevention of unintentional and road transport-related injury among adolescents to identify the evidence for effective injury prevention efforts. This review found studies were overwhelmingly from high-income countries, a high proportion of interventions targeted sports injury prevention, and there was low consideration of equity.

The predominance of studies evaluating injury prevention interventions for adolescents in high-income countries does not reflect the global injury burden. The Global Burden of Disease (GBD) Study indicates significantly higher deaths and DALYs due to road transport and other unintentional injury among adolescents in low-income countries, with the burden declining as income levels rise (Peden et al., 2022). Consistent with the socioeconomic gradient in injury risk (Yuma-Guerrero et al., 2018; Goldman et al., 2018), it was disappointing how few studies adequately considered the contribution of equity when evaluating interventions, even in relation to gender, which was only reported in two thirds of studies. Similarly, no studies evaluated injury prevention interventions for First Nations adolescents, despite known elevated rates of injury among these populations (Azzopardi et al., 2018). It is recommended that researchers, practitioners, and donors prioritize the development, implementation, and high-quality evaluation of interventions aiming to prevent or reduce transport and other unintentional injury among neglected adolescent populations such as First Nations adolescents, adolescents residing in low and middle income countries with LMICs, adolescents residing in regional and remote areas, adolescents with a disability, and adolescents of a culturally and linguistically diverse or low socio-economic background among others. Addressing such knowledge gaps about which interventions work to reduce injury among these populations at increased risk of injury-related harms will save lives.

At the same time, there may be economies of scale in implementing interventions known to be effective at reducing adoles-

Table 4
Injury prevention interventions for adolescent road traffic injury, grouped by effectiveness (n = 21).

Vehicle type (reference)	Evidence level	Outcome/ Severity	Intervention name	Age group (years)	Measures of effect	Direction of effect (↓↑-) *= statistical significance	Summary of impact
Bicycle (Ji et al., 2017)	III-I	Nonfatal	Road safety education	12–13	Incidence of bicycle injuries	↓*	In the intervention group, the incidence decreased significantly after the intervention (χ 2 = 8.137, p = 0.004), while no significant change was observed in the control group
Bicycle and Pedestrian (Inada et al., 2019)	III-I	Fatal; Nonfatal	Area-Wide Traffic-Calming Zone 30 Policy	15–24	Occurrence of fatal and serious injury	↓	Cumulative relative changes of and −0.19 (95% CI = −0.28, −0.090) in the rate ratio between September 2011 and December 2016.
Mopeds & scooters (Kosola et al., 2016)	III-2	Nonfatal	Driver education	15–16	Annual incidence	↓*	After the law change in 2011, the annual incidence of moped/scooter injuries among 15-year-olds in our area decreased from 0.8% in 2011 to 0.3% in 2013 (p < 0.001)
					Estimated incidence of injuries per new moped/scooter license	↓*	Estimated incidence of injuries per new moped/ scooter license declined from 1.8% in 2011 to 1.0% in 2013 (p = 0.001)
Motorcycle (Hassan et al., 2017)	III-2	Nonfatal	Motorcycle helmet legislation	<21 M age= 18.4	Motorcycle crash related traumatic Brain Injury-	↓*	Universal helmet legislations lowered the rate of MCC-related TBI injures by a factor of 2.15 (b coefficient: 2.15; 95% confidence interval: 0.91–10.18; P = 0.04).
Motor vehicle (Anderson, Carlson, & Rees, 2017)	IV	Nonfatal	Booster Seats	10–12	Any injury	↓	In children aged 10–12 years, the use of a booster seat was associated with a 33% reduction in the odds of any injury relative to being restrained by a seat belt alone (OR = 0.675, 95% CI = 0.505, 0.902).
Motor vehicle (Bonne et al., 2018)	III-3	Fatal	Graduated Driver Licensing (GDL)	16–20	Teen driver deaths (initiation of GDL)	-	No change in number of dead teen drivers (44 vs 49, p > 0.05)
					Teen driver deaths (GDL + comprehensive campaign)	↓*	After the comprehensive campaign, decreases are seen in dead teenaged drivers (42 vs 22, p < 0.05)
					Teenage passenger deaths in vehicles operated by another teen (GDL + comprehensive campaign)	↓*	Decreases in the number of dead teenaged passengers in a vehicle operated by another teen (19 vs 11p < 0.05).
Motor vehicle (Conner & Smith, 2017)	IV	Nonfatal	GDL	16–20	Motor vehicle crash related injury rates (16–17 years)	↓*	The post-GDL period was statistically associated with lower injury rates for occupants ages 16–17 years combined (RR = 0.94; 95% CI, 0.88–0.99).
					Motor vehicle crash related injury rates (18–20 years)	↓*	In addition, injury rates for occupants ages 18–20 years combined (RR = 0.75; 95% CI, 0.64–0.88) were statistically lower for the post-GDL period.
Motor vehicle (Fell, Jones, Romano, & Voas, 2011)	III-2	Fatal	GDL	16–17	Fatal crash involvements	↓*	The adoption of a GDL law of average strength was associated with a significant decrease in fatal crash involvements of 16- and 17-year-old drivers relative to fatal crash involvements of one of the 2 comparison groups (19–20 & 20–25).
Motor vehicle (Hirschberg & Lye, 2020)	III-I	Nonfatal	Signalling of the GDL system changes	18–25	Injuries requiring hospitalisation	↓	Resulted in around 6 less injuries requiring hospitalisation per month for females and around 7 less injuries requiring hospitalisation for males per month.
		Fatal			Fatalities	↓	For fatalities, these signals only had an impact for males of around 0.6 fewer fatalities per month.
		Nonfatal	Demerit points for traffic violations		Injuries requiring	↓	Demerit point system introduced for traffic violations

Table 4 (*continued*)

Vehicle type (reference)	Evidence level	Outcome/ Severity	Intervention name	Age group (years)	Measures of effect	Direction of effect (↓↑-) *= statistical significance	Summary of impact
					hospitalisation		in December 2002 only had a short-term impact of reducing injuries requiring hospitalisation of around 2 per month for males.
		Nonfatal	Extra year on "P plates" for those under 21 at time of licensing and to remain alcohol free while driving for the entire probationary period with peer passenger restrictions introduced for first year P platers		Injuries requiring hospitalisation	↓	approximately 5 fewer injuries for males and around 4 less injuries for females.
		Fatal			Fatalities	↓	around 0.8 less fatalities per month for males.
		Nonfatal	Stricter mobile phone restrictions for P platers		Injuries requiring hospitalisation	-	No impact on injuries requiring hospitalisation for either males or females.
		Fatal			Fatalities	↓	Around 1 less fatality per month for males and around half that effect for females
		Nonfatal	Minor modifications to the requirement of carrying a licence and the introduction of alcohol interlock measures for probationary drivers under the age of 26 found to be guilty of a Blood Alcohol Concentration over the limit.		Injuries requiring hospitalisation	↑*	For males we found a significant increase of around 4 injuries requiring hospitalisation per month
Motor vehicle (Kaafarani et al., 2015)	III-2	Fatal	GDL	16–17	Fatal motor vehicle crashes (fMVC)	↓*	The rates of fMVC decreased in the age group of 16 years to 17 years (from 14.0 to 8.6 per 100,000 people, p = 0.006),
				18–20		↓*	The rates of fMVC decreased in the age group of 18 years to 20 years (from 21.2 to 13.7 per 100,000 people, p < 0.001)
Motor vehicles (Males, 2013)	III-2	Fatal	GDL	16–25	Motor vehicle fatalities among car occupants	↑*	The 16–25 age group subjected to GDL suffered significant net increases of 7% in traffic fatalities compared to the control group not exposed to GDL. For the 16–25 age group as a whole, California's GDL was associated with approximately 60 more fatal crashes and fatalities per year.
Motor vehicles (Rouse et al., 2013)	III-2	Fatal	GDL	14–18	Fatal crashes	↓*	Rates of fatal crashes for 14- to 18-year-olds were reduced 59%. The largest decrease was found among 16-year-old drivers who evidenced a reduction in crashes of 22% (p < 0.001), followed by 17-yearolds at 13% (p < 0.001) and 18-year-olds at 8% (p < 0.001).
Motor vehicles (Toledo et al., 2012)	III-2	Nonfatal	GDL	17–24	Injury crash involvement	↓*	The crash rates of GDL participants are lower compared to non-participants by 12.7% (p < 0.05)
Motor vehicle (Ehsani et al., 2014)	IV	Fatal and disabling injury	Text messaging restrictions	16–24	Fatal and disabling injury change in crash rate (16 years)	-	No significant change.
					Fatal and disabling injury change in crash rate (17 years)	-	No significant change.
					Fatal and disabling injury change in crash rate (18 years)	-	No significant change.
					Fatal and disabling injury change in crash rate (19 years)	↑	Fatal and disabling injury crash rates increased by 0.43 crashes per 10,000 drivers.
					Fatal and disabling injury change in crash rate (20–24 years)	↑	Fatal and disabling injury increased by 0.32 crashes per 10,000 drivers
		Nonfatal and non-disabling injury			Non-disabling injury change in crash rate (16 years)	↑	Increased by 0.09 crashes per 10,000 licensed drivers

(continued on next page)

Table 4 (*continued*)

Vehicle type (reference)	Evidence level	Outcome/ Severity	Intervention name	Age group (years)	Measures of effect	Direction of effect (↓↑-) *= statistical significance	Summary of impact
					Non-disabling injury change in crash rate (17 years)	↑	After the introduction of the restriction, nondisabling crash rates increased by 0.75 crashes per 10,000 licensed drivers a
					Non-disabling injury change in crash rate (18 years)	-	No significant change.
					Non-disabling injury change in crash rate (19 years)	-	No significant change.
					Non-disabling injury change in crash rate (20–24 years)	↑	Nondisabling injury crash rates increased by 0.33 crashes per 10,000 drivers, respectively
Motor vehicle (Ferdinand et al., 2015)	III-2	Nonfatal	Text messaging bans	15–21	Motor vehicle injury-related hospitalisations	↓	Texting bans were marginally associated with MVC-related hospitalisations among those aged 15 to 21 years in sampled hospitals (IRR = 0.92; 95% CI = 0.84, 1.00; P = 0.081)
Motor vehicle (Fell, Scherer, Thomas, & Voas, 2014)	III-2	Fatal	Social host prohibitions (SHP)	<21	Underage drinking driver fatal crashes	↓	SHP laws were found to have a negative but nonsignificant impact on Fatality Analysis Reporting System ratios for drivers younger than aged 21
			Fake identification laws (FID)			↓*	For those drivers younger than aged 21 years, FID supplier laws were associated with significant decreases in Fatality Analysis Reporting System ratios after states adopted these laws (−1.0%, P = 0.030).
Motor vehicle (Scherer, Fell, Thomas, & Voas, 2015)	III-2	Fatal	Dram Shop, Responsible Beverage Service Training, and State Alcohol Control Laws	<21	The ratio of drinking to nondrinking drivers under age 21 involved in fatal crashes	↓*	Dram shop liability laws were associated with a 2.4% total effect decrease (direct effects: β = 0.019, p = 0.018). Similarly, RBS training laws were associated with a 3.6% total effect decrease (direct effect: β = 0.048, p = 0.001) in the ratio of drinking to nondrinking drivers under age 21 involved in fatal crashes.
Motor vehicle (Sherk et al., 2018)	IV	Nonfatal	Raised alcohol minimum prices	13–25	Emergency department presentations due to alcohol-related motor vehicle collisions	↓	Rates of ED visits among males aged 13–25 for MVCs decreased substantially during this study.
Motor vehicle (Richmond et al., 2016)	IV	Fatal	Criminal Law Amendment Act (Introduced Drinking & Driving Offences) (1969); Motor Vehicle Safety Act – Seat Belts Required in All New Vehicles (1971); Mandatory Seat Belt Laws in Ontario, Quebec, Saskatchewan and British Columbia (1976–1977); Amendments to Criminal Code – Tougher Penalties for Impaired Drivers (1985); National Occupant Restraint Program – Campaign to Increase Seatbelt Usage (1989); Graduated Licensing Programs Introduced in Most Canadian Jurisdictions (1994)	15–19	Change in injury mortality rates before and after specific interventions	↑	For 15–19-year-olds, there was a 408% increase in motor vehicle collision-related mortality rates between 1950 and 1971; however, a significant change in slope was noted during the period 1978–1985, compared to 1972–1977 (Est. = − 0.10, 95% CI = − 0.20, −0.007) across all age groups.
Motor vehicle (Layba et al., 2017)	III-I	Nonfatal	The Save A Life Tour (SALT) – safe driving awareness program	16–21	Nonfatal hospitalised injuries	↓*	A risk reduction of 37% (p < 0.05) in the number of adolescent motor vehicle crash-related injuries treated at a level 1 trauma centre
Road traffic injuries (Edwards et al., 2013)	III-3	Nonfatal	Free Bus Travel	12–16	Road casualty rates	↓	Road casualty rates declined, but the pre–post ratio of change was greater in young people than adults (ratio of ratios 0.84; 95% CI 0.82 to 0.87).

Abbreviations: ED = Emergency Department; GDL = Graduated Driver Licensing; ↓= reduced injury; ↑=increased injury;-= no change.

Table 5
Injury prevention interventions for other adolescent injury types (n = 7).

Injury type	Severity	Intervention	Evidence level	Country	Age group (years)	Outcome/Measures of effect	Direction of effect (↓↑-)	Summary of impact
Burns	Nonfatal	Firework laws (Myers & Lehna, 2017)	IV	US	<21	Injury rate / 100,000	↑* (	19.6% increase in injury rate /100,000 (p = 0.019)
						Inpatient admissions	↑*	Increased proportion of injuries requiring inpatient admission (28.9% in 2006 to 50.0% in 2012, P < 0.001)
						Mean length of hospital stay	↑*	Longer mean length of hospital stay (3.12 days in 2006 to 7.35 days in 2012, P < 0.001).
Burns	Fatal	Hazardous Products Act – Children's sleepwear & bedding flammability requirements; Child resistant lighters regulation & labelling requirements (Richmond et al., 2016)	IV	Canada	10–14	Change in slope in injury mortality rates before and after specific interventions	-	+0.02 change in slope (95% CI: 0.003–0.03)
Falls	Nonfatal	Raised alcohol minimum prices (Sherk et al., 2018)	IV	Canada	13–25	Emergency department visits alcohol-related falls	-	No change.
	Nonfatal	School based education program (Nauta et al., 2013)	II	The Netherlands	7–12 (M = 10.7)	Injury rate	↓	Injury incidence density (IID) of 0.14 fall-related injuries per 1000 h of physical activity (95% CI 0.09 to 0.18) for intervention, compared to 0.26 (95% CI: 0.21 to 0.32) for control.
	Nonfatal	Home Injury Prevention Intervention (HIPI) (Keall et al., 2015)	II	New Zealand	10–19	Falls requiring medical treatment	↓	0.007 mean annual injury rate (intervention) and 0.028 (control).
Firearm injury*	Nonfatal	Gun control laws comparing lenient vs strict states (Tashiro et al., 2016)	III-3	US	<20	Hospital admission for firearm injury	↑* (lenient states)	Lenient states had a proportionally higher rate of accidental injury (31%) versus strict states (17%), p < 0.001.
	Fatal					In-hospital mortality	↑* (lenient states)	On 1:1 propensity score–matched analysis, in-hospital mortality by case was higher in lenient (7.5%) versus strict (6.5%) states, p = 0.013.
All injury (unintentional + transport)	Nonfatal	Community coalition training (Berecki-Gisolf et al., 2001–2017. 2020)	III-2	Australia	10–14	Municipal rates of hospital admission for all injury	↓*	Compared to phase 0 – implementation (20–34yrsref) RR 1.05 (95% CI: 0.98–1.12), lower risk of injury at second cycle (phase 6) RR:0.92 (0.86–1.00) (p < 0.05)
					15–19		↓*	Compared to phase 0 – implementation (20–34yrsref) RR 1.01 (95% CI: 0.95–1.08), lower risk of injury at second cycle (phase 6) RR:0.90 (0.84–0.98) (p < 0.05)
Unintentional injuries					10–14	Municipal rates of hospital admission unintentional injury	↓*	Compared to phase 0 – implementation (20–34yrsref) RR 0.97 (95% CI: 0.90–1.04), lower risk of injury at second cycle (phase 6) RR:0.90 (0.83–0.97) (p < 0.05)
					15–19		↓*	Compared to phase 0 – implementation (The World Bank, 2022; Australian Government National Health and Medical Research Council (NHMRC), 2005; Aromataris, 2020; Achenbach et al., 2018; Åkerlund et al., 2020; Åkerlund et al., 2022; Anderson et al., 2017; Baker et al., 2016; Barboza et al., 2019; Bello et al., 2011; Berecki-Gisolf et al., 2001–2017. 2020,; Bollars et al., 2014; Bonne et al., 2018; Chena et al., 2019; Collard et al., 2010) RR 0.98 (95% CI: 0.91–1.05), lower risk of injury at second cycle (phase 6) RR:0.91 (0.83–0.99) (p < 0.05)

Abbreviations: AOR = Adjusted Odds Ratio; OR = Odds Ratio; RR = relative risk. Note: * reports intentional and unintentional injury, findings relevant to unintentional injury only extracted. Abbreviations: C = Control; T = Treatment US = United States of America. ↓= reduced injury; ↑ = increased injury; - = no change.

cent injury-related harms in HIC contexts, to LMICs. However, it will be vital to ensure appropriate adaptation to suit differences between settings, including available resources and cultural considerations (Stevenson et al., 2008). Alternatively, researchers should consider the development of interventions that are relevant to both HICs and LMICs simultaneously through partnership (Baker et al., 2022).

The largest body of evidence on the evaluation of adolescent injury prevention interventions was for sports injury where high quality evidence, commonly in the form of RCTs is available, albeit with the majority from high-income contexts. Soccer (football) was the sport most commonly addressed, with the vast majority of interventions comprising neuromuscular training, such as the FIFA 11 program. Evidence indicates investment in neuromuscular training, combined with strategies to encourage high adherence, will be effective in reducing injuries (such as those to the lower extremities) for a range of sports in addition to football including basketball (Emery et al., 2021; Foss et al., 2018; Longo et al., 2012), field hockey (Barboza et al., 2019), handball (Achenbach et al., 2018), track and field (Mendez-Rebolledo et al., 2021) and volleyball (Foss et al., 2018). Evidence also supports policy changes to reduce injury risk, in particular disallowing body checking in ice hockey for younger adolescents (ages 11–17 years) (Emery et al., 2022; Lacny et al., 2014). The evidence also indicates equipment such as shoulder braces and lace-up ankle braces can reduce sports injury risk among adolescents (Baker et al., 2016; McGuine et al., 2011). However, evidence gaps remain, including many popular sports not evident in this review (such as running and swimming (Hulteen et al., 2017), for adolescent girls and gender diverse youth. In addition, it is recommended that further high-quality research be conducted to identify effective interventions to prevent sports injuries in adolescents in low and middle income countries with LMICs settings and among First Nations adolescents.

Participation in sports brings a range of public health benefits (Malm et al., 2019; Guddal et al., 2019), and while sports injury generally poses low threat to life, it can significantly burden the health system (Emery & Pasanen, 2019). While evaluation of sports injury prevention interventions is valuable, better understanding of effective injury prevention is needed for high threat to life injury mechanisms, such as road traffic injury and drowning. The latter is the leading cause of unintentional injury-related mortality, and the third leading cause of DALYs globally for adolescents 10–24 years of age (Peden et al., 2022). Disappointingly this review yielded no evaluated interventions. A lack of research into effective drowning prevention interventions is indicative of the lack of investment in adolescent health more broadly, with evaluation of interventions - and subsequent investment in those interventions - lagging behind that of younger children (Peden et al., 2021; Li et al., 2018).

Similarly, despite being the leading cause of death and disability for adolescents, evaluation of road transport injury interventions was only reported in 21 studies. Strikingly, no studies evaluated interventions in low and middle income countries with LMICs. Many of the reported interventions targeted motor vehicle-related injury and used a legislative approach. Included studies indicated effectiveness of GDL schemes in reducing fatal and nonfatal motor vehicle-related injury Australia (Hirschberg & Lye, 2020), various U.S. states (Bonne et al., 2018; Conner and Smith, 2017; Fell et al., 2011; Kaafarani et al., 2015; Males, 2013; Rouse et al., 2013), and Israel (Toledo et al., 2012). As such, there is a reasonable body of evidence that indicates that GDL schemes are a recommended intervention to reduce fatal and nonfatal road transport-related injuries for adolescents. It is also apparent that the greatest effects come when integrating GDL schemes with other measures, such as comprehensive driver education (Bonne et al., 2018).

Despite the effectiveness of legislated approaches to reduce adolescent road transport injury, this review identified some unintended consequences of changes in legislation leading to increased injury risk. For example, relaxing age restrictions for purchasing fireworks led to an increase in burn injury among younger adolescents (Myers & Lehna, 2017), and higher firearm-related hospital admissions in U.S. states with more lenient gun control laws (Tashiro et al., 2016). Similar all-age experiences have been seen in the repeal of mandatory helmet wearing legislation, leading to an increase in traumatic brain injuries (Saunders et al., 2018), and lowering wages and benefits in the construction industry was associated with increased construction injury rates (Li, Zorigtbaatar, Pleités, Fenn, & Philips, 2019). These likely unintended consequences suggest that changes in legislation should be carefully considered before any policy change is undertaken. This includes a careful assessment of uneven or inequitable impacts such as the impact of firearm injuries on younger adolescents and the increased risk of occupational injury among poorer workers.

Although few studies reported the effectiveness of interventions to prevent other unintentional injury among adolescents, there are several high-quality studies that provide support for investment in interventions found to be effective. RCTs indicate significant reductions in fall injuries for 7–12 year-olds via a school-based education program in the Netherlands (Nauta et al., 2013), and fall injuries requiring medical treatment among 10–19 year-old New Zealanders after home modifications (Keall et al., 2015). Again, further well-designed studies are needed to identify effective interventions to address other unintentional injury mechanisms, as well as for wider populations such as First Nations adolescents and adolescents in low- and middle-income countries.

The authors encourage donors and governments to both support research to fill knowledge gaps, as well as use the available evidence to build an investment case for adolescent injury prevention. Evidence already exists as to the economic benefits of investing in a range of adolescent health and wellbeing initiatives (Sheehan et al., 2017), including road traffic injury prevention (Symons, Howard, Sweeny, Kumnick, & Sheehan, 2019). However, more work is needed to build the investment case around the economic benefits of preventing other unintentional injury among adolescents, and to do that, evidence of effective interventions is required.

In the absence of, or in addition to available evidence, the authors also encourage donors to consider in these investment cases, the broader economic gains associated with social, health, and environmental benefits of injury prevention interventions. These include environmental and physical health benefits associated with public and active transport (Filigrana-Villegas, Levy, Gauthier, Batterman, & Adar, 2019), the physical and mental health benefits of safe participation in sport (Finch & Owen, 2001), and the dual benefit of drowning risk reduction and opportunity for low impact physical activity that comes from learning to swim (Langendorfer, 2011), as well as their valuable role in helping countries to achieve a range of Sustainable Development Goals (Ma et al., 2020).

Preventing injury among adolescents can be challenging, which may in part explain why injury prevention efforts have traditionally focused on younger children and adults (Rivara, 2012; Patton et al., 2012). Adolescence is characterized by rapid physical, mental, social, and emotional change (Patton et al., 2016). This results in a developmental transition point for injury risk, with increasing independence seeing a shift from parental to peer supervision, licensed driving, and legal alcohol consumption, as well as sensation seeking leading to risk-taking behavior (Ward et al., 2021;

Curtin et al., 2018). Therefore, injury prevention interventions must be adjusted for this stage of human development. These adjustments will be powerful, as interventions aimed at improving health and wellbeing during adolescence have been shown to flow into adulthood and onto the next generation (Patton et al., 2016).

This review has synthesized information regarding effective unintentional injury prevention interventions for adolescents, which can inform the economic assessment of the cost/benefit of implementing effective interventions. Such information is vital to encourage government and donor investment in injury prevention for adolescents. However, the findings of this review must be considered within the context of some limitations. The focus of this review was interventions specifically impacting injury among adolescents aged 10–24 years. This excludes interventions known to be effective at reducing injury among the general population (i.e., seat belts, speed cameras, gun control legislation). Excluding self-reported injury may have biased against the inclusion of studies from resource poor settings as these countries may lack formal injury reporting systems. This review was conducted in the English language only and may have therefore excluded studies published in languages other than English. This review included original research published in peer-reviewed literature only; additional evidence may exist in the grey literature, doctoral dissertations or other unpublished documents. Although a detailed search strategy was used, the omission of terms such as 'students,' 'college/uni versity' and 'high school/secondary school' may have impacted the literature identified. Finally, due to the heterogeneous nature of the interventions and analyses used in the included studies, quantitative synthesis of the results was not possible and, although not the initial intention, a meta-analysis was not conducted.

5. Conclusion

Unintentional injury, including road traffic injury, is the leading cause of death and disability among adolescents, with a disproportionate burden in low and middle income countries with LMICs. Evidence regarding effectiveness of interventions can inform investment decisions to reduce injury-related harm, however the evidence does not currently reflect global burden, nor adequately reflect those groups at increased risk. Additionally, while this review yielded a significant body of literature on less lethal injury mechanisms (i.e., sport), there was a total absence of evidence to inform the prevention of adolescent drowning, a leading cause of unintentional injury deaths among 10–24-year-olds globally. With little change in adolescent deaths and DALYs due to injury globally in the last three decades, further research and investment in effective injury prevention interventions for this age group are urgently required.

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7. Implications and Contributions

This study provides evidence to support investment in effective injury prevention interventions for adolescents. However, outside of high-income settings and for injuries other than sport injuries, there are significant evidence gaps regarding effective unintentional injury prevention interventions for adolescents. Future research must also give greater consideration to more disadvantaged adolescents.

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.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jsr.2023.03.005.

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Dr Margie Peden Margie's work focuses on how to prevent unintentional injuries, particularly in resource-strapped countries. While road injuries are the biggest issue, Margie's work also canvases other significant problems of drowning, burns and falls, and identifies interventions that could save lives. Her research looks at what works, specifically in developing countries. It will provide evidence on how to prevent injuries before they happen. But it will also hope to look at the post-crash phase, working with nurses – who are the mainstay of healthcare provision in developing countries – to provide optimum treatment management. In some developing countries, traumatic injuries account for up to 70%-80% of the caseloads in emergency rooms. If you can stop these injuries upstream, there are enormous gains for healthcare systems, both financially and in terms of workforce needs. Representing The George Institute for Global Health and South Africa, Margie is a member of the Commonwealth Road Safety Initiative Expert Panel and together with colleagues from Kenya and Canada leads the data analysis for the reports being developed ahead of the 3rd Ministerial level meeting in Sweden in February 2020 and the CHOG meeting in Rwanda. She is also a member of the Academic Expert Group for this Ministerial meeting, a group responsible for making an independent and scientific assessment of the progress made during the Decade of Action for Road Safety. This report is now available here. The Academic Expert Group will also recommend a road safety strategy for the period 2020-2030. Margie is also Chair of the Global Advisory Board for the Malawi Road Safety Research and Implementation Unit at the University of Malawi. Prior to working at The George Institute, she was a nurse and an epidemiologist. She worked in a hospital in Cape Town, South Africa for many years before moving to the National Trauma Research Programme at the South African Medical Research Council. After that she was at the World Health Organization for 17 years, coordinating the Unintentional Injury Prevention unit.

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Constructs of leading indicators: A synthesis of safety literature

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ABSTRACT

Introduction: Leading indicators represent an invaluable tool that offer organizations the capability to: track health and safety performance, not just failures and accidents; measure effectiveness of safety efforts adopted; and focus on undesired precursors, rather than undesired occurred events. Despite these palpable advantages associated with their adoption, leading indicator's definition, application, and function are mostly ambiguous and inconsistent within literature. Therefore, this study systematically reviews pertinent literature to identify the constructs of leading indicators and generates guidance for leading indicator implementation (as a conceptual model). *Method:* The overarching epistemological design adopted interpretivism and critical realism philosophical stances together with inductive reasoning to analyze 80 articles retrieved from the Scopus database, plus 13 more publications supplemented by the snowballing technique. Analysis of the safety discourse within literature (as secondary data) was undertaken in two stages, namely: (1) a cross-componential analysis identified the main features of leading indicators in comparison to lagging indicators; and (2) content analysis revealed prominent constructs of leading indicators. *Results and conclusion:* Analysis results identify that the definition, types, and development methods represent the main constructs for understanding the concept of leading indicators. The study identifies that ambiguity around the definition and function of leading indicators is due to the lack of differentiation of its types, namely passive leading indicators and active leading indicators. *Practical application:* As a practical contribution, the conceptual model, which introduces continuous learning through a perpetual loop of development and application of leading indicators, will help adopters create a knowledge repository of leading indicators and to continuously learn and improve their safety and safety performance. Specifically, the work clarifies their difference in terms of the timeframe passive leading indicators and active leading indicators take to measure different safety aspects, the functions they serve, the target they measure and their stage of development.

1. Introduction

> *"You cannot teach a man anything, you can only help him find it in himself"- Galileo Galilei CE: 1564 -1642*

The introduction of Safety-I and Safety-II concepts in safety science has changed conventional understanding of safety, its metrics, measured elements, and approach to preventative measures accordingly (Patriarca et al., 2019). Safety-I defines safety as an absence of failure (or negative outcomes) and attempts to minimize accident occurrence (Sujan et al., 2019), whereas Safety-II describes safety as the presence of positive outcomes and strives to sustain safety by measuring and learning from '*what went right*' (Hollnagel, 2014). Scholars in safety management literature might disagree on one unequivocal definition of safety (namely, the absence of failure or presence of success), however all safety management theorists and practitioners agree that measuring and maintaining safety is intrinsically important for all stakeholders in safety practice (Floyd, 2021). Hence, various prominent scholars (cf. Hallowell et al., 2020; Elsebaei et al., 2020; Erkal et al., 2021; Schwatka et al., 2016) offer a plethora of indicators and metrics that are designed to inform the status of safety at a given time (either before or after an accident) to enable prevention of unfavorable events' occurrence or reoccurrence. Measuring safety of the past is achieved through investigation and analysis of factors in historical incidents, also known as lagging indicators (Almost et al., 2019; Jazayeri & Dadi, 2017). Studying lagging indicators

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enables the identification of '*what went wrong*' in the system, so that past failures, errors, and mistakes can be prevented in the future (Erkal et al., 2021). Examples of lagging indicators include: recordable injury rate (Floyd, 2021); employers' liability compensation costs (Costin et al., 2019); lost work day rate (LWDR) (Falahati et al., 2020); experience modification rate (EMR) (Jazayeri & Dadi, 2017); and fatality rate (Hinze et al., 2013). Outcomes derived from analyzing lagging indicators serve as a foundation for developing preventative measures for future projects (Elsebaei et al., 2020; Sinelnikov et al., 2015).

However, numerous academics (mostly Safety-II proponents) question the efficiency or accuracy of lagging indicators to measure safety or indeed to predict future safety performances (cf. Grabowski et al., 2007; Alruqi & Hallowell, 2019; Yorio et al., 2020; Xu et al., 2021). This growing notoriety of lagging indicators is ascribed to their erroneous external (outside the company) misuse in the form of benchmarking indicators or contractors' selection criteria (Elsebaei et al., 2020). Such practices change the organizational psychology from using lagging indicators for introspection, learning and prevention purposes, towards exercising record-keeping for performance demonstration purposes only, which in turn triggers the manipulation of recording and generation of spurious accident events reporting (Xu et al., 2021). In contrast to measuring safety in/of the past (using lagging indicators), there is a range of proactive safety metrics used to measure current safety status in a timely manner (e.g., safety culture, safety risk analysis, leading indicators, safety climate) (Elsebaei et al., 2020; Tang et al., 2018) - amongst which leading indicators are commonly contrasted with lagging indicators (cf. Alruqi & Hallowell, 2019; Xu et al., 2021). In recent literature, this duo of lagging and leading indicators is also referred to as reactive and proactive, trailing and leading, downstream and upstream, historical and predictive, trailing and heading, negative and positive indicators, respectively (cf. Sinelnikov et al., 2015; Haas & Yorio, 2016; Xu et al., 2021). Leading indicators are defined as the predictive and proactive measurement of safety that enable safety status monitoring without waiting for a system to fail and reveal its weaknesses (Eaton et al., 2013). Leading indicators seek to measure organization's safety status by monitoring its long term, safety related practices and short-term, current (negative or positive) manifestation of such practices in real time (Falahati et al., 2020). This ensures that relevant actions can be undertaken to prevent negative outcomes or continue positive actions leading to success (Patriarca et al., 2019). However, despite the popularity and potential advantages of leading indicators, its definition, types, applications, functions, and elements (i.e., measurements adopted to be a leading indicators) described in extant literature are mostly equivocal and inconsistent (cf. Alruqi & Hallowell, 2019; Guo & Yiu, 2016; Sinelnikov et al., 2015; Sheehan et al., 2016). Moreover, the distinctiveness of every organization's safety management system(s), safety culture maturity level, as well as different capacity and resources allocated to develop, measure, and record the leading indicators make the elements and application of leading indicators non-generalizable and unique to every organization and individual project (Xu et al., 2021).

Hence, the following research question is framed *viz.,* what are the main leading indicator constructs that enable clear explanation of such concept and facilitate their wider adoption for proactive safety management? Therefore, this study systematically reviews the prevailing academic discourse within pertinent literature on safety leading indicators to determine their constructs, that is, components that define them. Moreover, the work presents a conceptual model of leading indicator development and application that serves as essential theoretical guidance for organizations to develop, adopt, and implement leading indicators as their proactive safety monitoring practice. Such a model will augment organizations' transformation into continuous learning entities by collecting and recording the data about safety status and safety performance in their knowledge repository. Associated objectives are to: identify the main features of safety leading indicators in contrast to safety lagging indicators using a cross-componential analysis; and generate a new theory-based guidance note of leading indicator implementation that will clarify the definition, function, development process, and potential use of leading indicators in safety management. Cumulatively, this work provides an invaluable contribution to contemporary academic discourse on proactive safety management by clarifying the complexities of leading indicators and paves the way for future studies to focus on the differences of active leading indicators (ALIs) and passive leading indicators (PLIs) and their prospective use in proactive safety management.

2. Methodology

To determine the main features of leading indicators and generate a conceptual model for leading indicators' development, a comprehensive review of pertinent literature is undertaken, where each publication represents a unit of analysis and secondary data source (Posillico et al., 2021). An overarching epistemological stance that combines critical realism and interpretivism (augmented by inductive reasoning) is adopted for successful achievement of the study's objectives (Burton et al., 2021; Edwards et al., 2021; Roberts et al., 2019). Interpretivism explains and interprets a phenomenon under investigation from different perspectives in a subjective way, whereas critical realism entails using objectivity to enhance critique and appraisal of analysis undertaken (Clark et al., 2021). At stage one, a cross-componential analysis of leading and lagging indicators was performed utilizing critical realism to reveal distinctive features of both indicators by comparison. Cross componential analysis is a process of dividing the sense of a word or concept into its minimal distinctive features (i.e., semantic components) in contrast to another word or concept (Widyastuti, 2016). Componential analysis strives to dissect the inferential, implicational, and core meaning of two or more words and concepts (or lexemes) being analyzed, by identifying and comparing their semantically related common and distinctive components (Widyastuti, 2016).

Data for the analysis is sourced from the Scopus database with the search rules of TITLE-ABS-KEY ("leading indicators") AND TITLE-ABS-KEY ("safety management") to remain consistent with the study's aim and objectives. These specific search keywords were selected and no filter or exclusion criteria were applied in order to study the current status of leading indicators literature. The Scopus database was utilized for this research primarily because it has a broader coverage of literature when compared to alternative databases (i.e., Web of Science, PubMed and Google Scholar) (cf. Kukah et al., 2022). Moreover, Scopus was also chosen because it: contains automated analytical tools for summary analysis of search results; allows comma-separated value (CSV) file download of bibliometric details of publications; and has been extensively utilized in similar studies (Li et al., 2014). The main disadvantage of using Scopus is that other relevant publications may not be included in the search (cf. Falagas et al., 2008) but this issue can be mitigated via the use of snowballing (cf. Li et al., 2020). The initial search rules produced 151 publications (refer to Fig. 1). Most studies (31.4% or frequency (f) = 91 documents) were from the Engineering discipline, followed by (in descending order): Chemical Engineering (15.2% or f = 44 documents); Medicine (14.5 % or f = 42 documents); and Social Sciences (9.3% or f = 27 documents). These search results indicate that studies on leading indicators are multidisciplinary and significantly pervasive in safety–critical

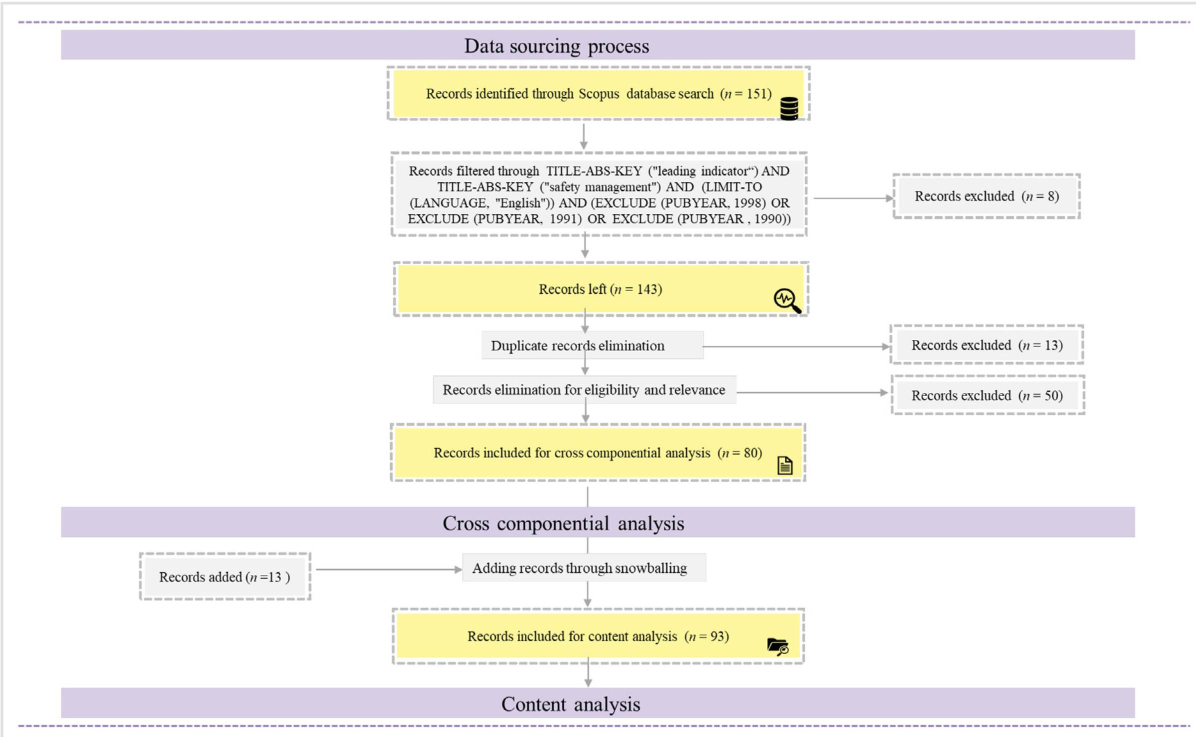

Fig. 1. Data selection steps for two-staged analyses.

industries such as construction, civil engineering, chemical and petrochemical industries, and healthcare sector. The earliest publication year of sourced studies commences from 1990 and the most prolific year of leading indicator studies is in 2020 with 19 documents.

To focus onto the most relevant publications, filters were subsequently applied with the search rules TITLE-ABS-KEY (‘‘leading indicator”) AND TITLE-ABS-KEY (‘‘safety management”) AND (LIMIT-TO (LANGUAGE, ‘‘English”)) AND (EXCLUDE (PUBYEAR, 1998) OR EXCLUDE (PUBYEAR, 1991) OR EXCLUDE (PUBYEAR, 1990)), which refined the results to 143 publications. Subsequently, to maintain the recency and pertinence of sourced papers to the research topic, years of publication were limited to 2000–2022 (where 2022 includes only publication available at the time of sourcing). Bibliometric data sourced from Scopus is in CSV format and includes the details of ‘authors,’ ‘year of publication,’ ‘DOI,’ ‘abstract,’ ‘authors’ keywords,’ and ‘index keywords.’ Through manual cleansing of duplicates (which excluded 13 records) 140 papers were selected for full-text sourcing. The final step of selection criteria was based on publications’ length and eligibility by using the digital object identifier (DOI) detail published with each item, followed by manual screening of abstracts, to assess their relevance to the study’s aim and objectives. As a result, 80 publications were selected for cross-componential analysis.

During stage two, the snowballing technique was adopted by examination of references found in this initial sample of 80 papers. Snowballing is especially useful for: extending the initial results of a systematic literature review; and ensuring a wide coverage of relevant publication materials is captured for subsequent analysis (cf. Greenhalgh & Peacock, 2005). Consequently, 13 more relevant publications were sourced from the initial 80 papers and a total of $f = 93$ documents were added for subsequent content analysis. The content analysis (as well as preceding cross-componential analysis) was conducted using computer-assisted qualitative data analysis software (CAQDAS) called – NVivo to deliver a richer interrogation of the prevailing academic discourse. Content analysis scrutinizes the meanings, contexts, and intentions contained in the analyzed document (Prasad, 2008) to draw replicable and valid inferences from the units of analysis by clustering closely related contents into categories. The emergent results from content analysis generate new insights, knowledge and representation of facts (Elo & Kyngäs, 2008). Therefore, complementing the second stage of analysis with relevant works (via the snowballing technique) was necessary to achieve a comprehensive scrutiny of the definition, types, and methodologies used for leading indicators’ development.

The development of new understanding in content analysis is performed through inductive reasoning. A notable limitation associated with developing a new theory using inductive reasoning is that it requires deductive testing in practice to confirm validity (or otherwise) (cf. Wacker, 1998; Sidiropoulos, 2021). That said, theoretical development is the bedrock upon which new knowledge is propagated and subsequently tested and has received extensive applications in contemporary scientific literature (Wacker, 1998).

3. Measuring and maintaining safety: Safety performance indicators

Unlike lagging indicators, the definition, nature, identification process, and utility of leading indicators have failed to reach a consensus in theoretical and practical terms (Guo & Yiu, 2016; Haas & Yorio, 2016; Jazayeri & Dadi, 2017; Xu et al., 2021). Alruqi and Hallowell (2019) ascribe scant leading indicator studies to the lack of resources and the difficulty in objectively accessing the large volume of sensitive organizational data. Similarly, Mearns (2009) highlights that despite an abundance of data (*i.e.*, records of safety performance) being collected in organizations, limited knowledge of how to effectively use the data for safety improvement obstructs the application of leading indicators. However, Oswald (2020) states that the adoption of these concepts (leading and lagging indicators) from the economics discipline to safety management without due rigorous consideration is a major source of confusion amongst safety academics.

3.1. Relationship of leading and lagging indicators

To define leading indicators, many studies (cf. Alruqi & Hallowell, 2019; Hopkins, 2009; Podgórski, 2015; Sheehan et al., 2016) suggest contrasting the nature, function, and focus of leading indicators with lagging indicators. Some studies on these indicators describe the relationship of leading and lagging indicators as a continuum (Reiman & Pietikäinen, 2012); whereas others describe it as relative (Dyreborg, 2009), negative (Haas & Yorio, 2016), bidirectional (Kongsvik et al., 2010) or time dependent (Yorio et al., 2020). Other scholars (cf. Saqib & Siddiqi, 2008; Mearns, 2009; Øien et al., 2011; Murray, 2015; Swuste et al., 2016; Neamat, 2019) view the relationship of these indicators as undistinguishable, overlapping, and blurred and hence, both indicators are collectively referred to as process safety indicators (Swuste et al., 2016), safety performance indicators (dos Santos Grecco et al., 2014; Saqib & Siddiqi, 2008), or key performance indicators (Murray, 2015; Yorio et al., 2020). For example, Wurzelbacher and Jin (2011) attempt to develop a framework for evaluating occupational safety and health (OSH) program effectiveness using leading and trailing metrics. Similarly, Haas and Yorio (2016) develop 22 performance measurements that combine leading and lagging indicators, and categorize them as worker performance, organizational performance, and interventions indicators. Furthermore, other studies on the interrelationship between these indicators have developed models and frameworks that explicate the indicators' relationship based on severity and predictability of occurrence (Swuste et al., 2016, 2019). The Bowtie diagram represents a prominent visual metaphor that describes the sequential relationship of leading and lagging indicators in relation to accident occurrences (Swuste et al., 2016). The Bowtie's center is depicted as an accident or other unfavorable event, the left side demonstrates barriers targeted to prevent hazards (*i.e.*, primary prevention), whereas the right side represents consequences and activities designed to minimize incident severity (*i.e.,* secondary and tertiary prevention; Wurzelbacher & Jin, 2011; Swuste et al., 2019). In this metaphor, leading indicators (on the left side of the Bowtie) reveal any gaps or faults of preventative measures and barriers adopted, whereas lagging indicators describe the consequences of that undesirable event or accident (Schmitz et al., 2021). Based on this explanation, Swuste et al. (2016) describe leading indicators as proxies for barriers, hazards, and management factors that inform the cases of process deviations or the stability of a safe system of working. In contrast, lagging indicators are proxies for the event at the center and consequences Swuste et al. (2016). Similarly, the Safety Pyramid (developed in process safety management studies) represents another schematic representation of two indicators' relationship and delineates four levels of event occurrences, each increasing in severity from the pyramid's bottom to top (Murray, 2015; Stauffer & Chastain-Knight, 2021; Swuste et al., 2016). The pyramid's lower level is tier 4 type leading indicators representing minor severity level events, known as challenges to safety management systems, which are followed by tier 3 leading indicators that are near miss occurrences (Murray, 2015; Stauffer & Chastain-Knight, 2021; Swuste et al., 2016). The top two levels are described as lagging indicators of which the last tier 1 level represents the events with the most severe consequences (Murray, 2015; Stauffer & Chastain-Knight, 2021; Swuste et al., 2016).

3.2. Elements of safety performance indicators

Both alluded models of safety performance indicators (*i.e.*, Bowtie and Safety Pyramid) highlight the complementary and inseparable relationship of both leading and lagging indicators and their pivotal role in providing critical information on the status of safety within an organization (and/or satellite sites managed), as well as revealing the efficiency/inefficiency of adopted safety management systems (Øien et al., 2011). The virtually indistinguishable relationship between lagging and leading indicators is emphasized by several scholars (cf. Kongsvik et al., 2010; Haas & Yorio, 2016; Yorio et al., 2020) who note that lagging indicators can explain the efficiency of leading indicators. In this case, the relationship of indicators appears bidirectional or reverse causational and their function is interchangeable (Kongsvik et al., 2010; Haas & Yorio, 2016; Yorio et al., 2020).

However, the relationship between leading and lagging indicators becomes even more blurred when elements of indicators (such as near misses, safety climate, or frequency of toolbox meetings) are studied. A leading indicator element here, denotes specific quantitative or qualitative measurements/indicators with preventative or affirmative property that are developed and adopted by an individual company to monitor safety. According to Haas and Yorio (2016) and Oswald *et al*., (2020) some elements can be considered lagging or leading indicators depending on the focus and purpose of measurement (e.g., a near miss can serve as a leading indicator if it predicts a severe future event; Sheehan et al., 2016). Yet focusing on the event (near miss) as a minor severity level incident that has already occurred, will render the event as a lagging indicator (Murray, 2015). Table 1 provides examples of leading indicator elements (on the second column), aggregating them as groups (on the first column) by their description in pertinent literature.

Table 1 illustrates that other known proactive measurements of safety (e.g., safety climate, safety culture and near miss occurrences) appear as safety leading indicator elements (Alruqi & Hallowell, 2019), since they are all associated with measuring the status or the strength of safety (Erkal et al., 2021; Xu et al., 2021). Most leading indicators' elements represent practices of safety management systems (e.g., adopting zero injury technique, substance abuse program or safety training), which highlights the main function of leading indicators to measure the efficiency of policies, rules, and preventative steps of organizational safety management. However, leading indicators elements mentioned by every study in the 'safety management systems element' group are multifarious and distinctive from every other example, since a safety management system of each individual organization is unique and contextual (Xu et al., 2021).

3.3. Classifications of leading indicators

These elements of leading indicators (exemplified in Table 1) are broadly divided into two common dichotomous classifications *viz*.: (a) based on their stage of adoption, *active* and *passive* leading indicators (cf. Hinze et al., 2013; Jazayeri & Dadi, 2017); and (b) based on their function, *structural* and *operational* leading indicators (Falahati et al., 2020). According to Hinze et al. (2013), PLIs take a long time to measure, while ALIs can be measured within a shorter time period. In other words, PLIs are a manifestation of decisions, actions, or events that have taken place long before the operation or project has been initiated (*i.e.*, the design stage); whereas ALIs are a manifestation of decisions, actions, or events that have taken place during the operation or project and, hence, can be timely corrected once observed Hinze et al. (2013). Examples of PLIs include: a steel-toed boots policy (Alruqi & Hallowell, 2019); the percentage of management personnel with 10-hour or

Table 1
Leading indicator descriptions in the literature.

Leading indicator described as…	Examples of leading indicator elements	Citations
Safety management system element	Alcohol/ drug testing; attitudes and safety climate; housekeeping; safety behavior of safety; fall protection; training and job safety talk; near misses; safety correction; safety inspection; and subcontractor safety.	Neamat, 2019
	Worker observation process; near miss reporting; project management team safety process involvement; job site audits; stop work authority; housekeeping program; and safety orientation and training.	Elsebaei et al., 2020
	Safety training; ergonomic opportunities identified and corrected; reduction of musculoskeletal disorder (MSD) risk factors; employee perception surveys; and safety audits.	Hughes & Ferrett, 2020
	Zero injury techniques; demonstrated management commitment; staffing for safety; pre-project and pre-task planning; safety education and training; employee involvement; safety recognition and rewards; incident investigations; substance abuse programs; and subcontractor management.	Hallowell et al., 2013
	Near misses; safety audits; safety culture; and safety climate measures.	Eaton et al., 2013
	Upper management involvement; training/orientation; pre-task safety meeting; safety inspections/ observations; hazard and accident analysis; owner involvement; safety record; worker involvement; safety resource; staffing for safety; written safety plan; personal protective equipment (PPE); substance abuse; and incentives.	Alruqi & Hallowell, 2019
	Safety climate;	Zohar, 2010; Schwatka et al., 2016
Safety hazard and risk perception surveys	Questionnaire-assessed safety hazards; and management practices.	Moore et al., 2022
	Survey of workers, regarding the human factor issues.	O'Connor et al., 2010
Safety culture	Accountability; consultation and communication; management commitment and leadership; audits and workplace OSH inspections; empowerment and employee involvement in decision making about OSH; positive feedback and recognition for OSH; prioritization of OSH; risk management and systems for OSH; and the provision of OSH training, information, tools and resources.	Sheehan et al., 2016
	Top-level commitment to safety; organizational learning; organizational flexibility; awareness; just culture; and emergency preparedness.	dos Santos Grecco et al., 2014
Safety status monitoring, recording and reporting practices	Information from a safety audit that can lead to systematic changes for safety, such as a change in equipment or procedure; A near miss report that explains a 'difficult to observe' unsafe action, such as fluid and momentary human error, that has readily been shared without fear of punishment; A safety walk report explaining a solved dynamic safety problem that unexpectedly arose on site; and A recorded safety observation that identifies and explains potential problems for upcoming high-risk activities, such as work at height.	Oswald, 2020
Organization's occupational health and safety (OHS) performance.	OHS leadership; OHS culture and climate; employee participation in OHS; OHS policies, procedures and practices; and OHS risk control.	Yanar et al., 2020
Assessment of adopted safety management system	Direct measures of safety management systems such as frequency or timeliness of audits.	Hopkins, 2009
Preventative measures	Activities, practices, and programs for preventing injuries and minimizing duration and severity of injuries when they do occur.	Moore et al., 2022

30-hour Occupational Safety and Health Administration (OSHA) certification (Jazayeri & Dadi, 2017); contract provisions that require subcontractor compliance with a site-specific safety policy or program (Hinze et al., 2013); and other safety management activities that are adopted prior to the project initiation stage. To a degree, PLIs are almost indistinguishable from *structural* leading indicators, which encapsulate all health and safety management efforts made by a company such as policies, objectives, and plans, procedures and guidelines (Cambon et al., 2006; Falahati et al., 2020). Similarly, there is an overlapping construct in the definition and examples of ALIs and *operational* leading indicators; where ALIs are described as a measurement of safety in real time and *operational* leading indicators are described as a measurement of the effectiveness of safety and health management systems in an operation stage (Falahati et al., 2020; Podgórski, 2015). Examples of ALIs include: quality of pre-job safety meetings (Alruqi & Hallowell, 2019); physical stress caused by overexertion (Costin et al., 2019); percentage of adherence to safety based on audits (Jazayeri & Dadi, 2017); and rate of involvement of upper management in safety walk-throughs (Hinze et al., 2013). These examples show that ALIs are monitored and measured both quantitatively and qualitatively. Quantification of ALIs is the most prevalent and conventional approach where safety management activities such as subcontractor safety audits, safety observations, and toolbox talks are measured in terms of frequency of occurrence (Swuste et al., 2016). However, many scholars (cf. Hopkins, 2009; Costin et al., 2019; Xu et al., 2021; Schmitz et al., 2021) argue that sole quantification of ALIs is insufficient and therefore, qualitative description and measurement of such indicators must be combined to establish a complete and in-depth picture of safety status. For example, a mere measurement of the frequency of toolbox talks fails to adequately explain the effectiveness, content, and quality of those toolbox talks, which can inadvertently promote the notorious 'box-ticking' approach in safety status measurement (Xu et al., 2021). Another drawback of only quantitatively measuring safety is that any positive or negative event(s) with low frequency and minor severity will remain statistically insignificant, in which case those records will not be recognized and the opportunity to learn from those occurrences will be lost (Floyd, 2021). Therefore, for holistic indication of safety performance and comprehensive monitoring of safety, quantification of safety activities must be accompanied with supplementary qualitative information (Floyd, 2021).

4. Findings

The ubiquity of lagging indicators implementation as a safety performance indicator by most organizations is ascribable to the ease of collecting, recording, and analyzing them (cf. Almost et al., 2019; Lingard et al., 2017). Numerous tools, theories and methods exist to analyze past events of reportable and recordable accident occurrences; epitomized by the fishbone diagram, five whys, root-cause analysis that attempt to determine cause(s) and underlying reasons of recorded accident cases, namely lagging indicators (Hughes & Ferrett, 2020). Whereas recent applications of machine learning and predictive/classification analytics (both stochastic or deterministic modeling variants) are more sophisticated methods that attempt to identify systemic vulnerabilities and determine accident predictors (Bortey et al., 2021; Erkal et al., 2021; Shrestha et al., 2020). However, studies on leading indicators reside within an incipient stage of development only (Mearns, 2009). The results of cross-componential analysis illustrated in Table 2 identify main components/features of both concepts (i.e., leading and lagging indicators). These include the focus, function, definition, underlying concept, risk assessment, what, and how metrics are measured as well as advantages and disadvantages.

Both leading and lagging indicators have their own merits in terms of the function they serve *viz.* in respective order: monitoring safety or unsafety (Reiman & Pietikäinen, 2012); measuring different level of precursors (e.g., safety behavior of workers and near misses) or consequences (e.g., near misses or dangerous occurrences) (Swuste et al., 2019); and responding by correcting in the moment or by learning after the occurrence and preventing them in the future (Hinze et al., 2013). Table 2 illustrates that most components used to contrast leading and lagging indicators differ for each indicator, except for five overlapping or common components (that are highlighted with light yellow shading in Table 2). These common components appear - once in *function and use* component (i.e., for external use of a company); once in *what they measure* (i.e., negative status of safety); once in *how they measure* (i.e., quantitatively); and twice in the *disadvantages* component, namely: (1) sole quantification-based safety performance indicators (i.e., leading and lagging indicators) fail to holistically indicate a safety performance; and (2) recording and analyzing only high severity and high frequency occurrences and ignoring seemingly statistically insignificant data obstructs the learning opportunity. The findings demonstrate that lagging and leading indicators emerge from two different safety concepts *viz.*, Safety-I and Safety-II, which (similar to the leading and lagging indicators) are frequently contrasted in safety science literature. However, like the Safety-II concept, the notion of a leading indicator is a relatively new concept in safety management that possesses some ambiguity around its functions, deviations in definition, and bear vagueness in implementation and application. Therefore, this drawback of leading indicators is explained (in Table 2) as being one of the main disadvantages that hinders the adoption of leading indicators.

Premised upon this finding, the content analysis stage focused on aggregating the themes of three main constructs of leading indicators that facilitate its explication *viz.*: (1) the definition; (2) clas-

Table 2
Cross-componential analysis of leading and lagging indicators.

Features	Leading indicators	Lagging indicators
Definition	Current situation that can affect future performance (Mearns, 2009).	Outcomes that result from our actions (Mearns, 2009).
	Precursors of failure or success (Swuste et al., 2016).	Occurrences of failures (Schmitz et al., 2021).
Examples	Safety culture, safety climate, near-misses, safety training, toolbox talks, safety training and orientation, safety inspections (Falahati et al., 2020).	Total recordable injury rate (TRIR), lost work day rate (LWDR), worker compensation rate (WCR), lost time cases (LTC) (Floyd, 2021; Jazayeri & Dadi, 2017).
Function and use	For monitoring and responding (Guo & Yiu, 2016).	For recording, reporting and learning from past mistakes (Alruqi & Hallowell, 2019).
	For internal use of a company (Reiman & Pietikäinen, 2012).	
	-	For external use of a company (Elsebaei et al., 2020).
Underlying concept	Safety-II and Resilience engineering (Patriarca et al., 2019; Pęciłło, 2020).	Safety-I (Hollnagel, 2014).
Risk assessment	Proactive and reactive (Sheehan et al., 2016).	Retrospective and introspective (Lingard et al., 2017).
Focus	Safety performance now and near future (Yorio et al., 2020).	Safety performance of the past (Alruqi & Hallowell, 2019).
	Safety status before accident occurrence (Haas & Yorio, 2016).	Safety status at the moment of accident (Neamat, 2019).
Measures (what)	Negative status of safety, i.e., absence of safety (Sheehan et al., 2016).	
	Negative and positive precursors: signs and signals of upcoming failure or success (Patriarca et al., 2019; Reiman & Pietikäinen, 2012; Xu et al., 2021).	Negative outcomes only: failures, errors, mistakes, accidents, near misses, dangerous occurrences (Lingard et al., 2017).
Measures (how)	Quantitatively (dos Santos Grecco et al., 2014).	
	Qualitatively (Reiman & Pietikäinen, 2012).	-
Advantages	Timely safety performance measure enables to prevent accident occurrences (Floyd, 2021).	Lesson learnt from the past enables data-driven and informed generation of preventative countermeasures (Oswald, 2020).
	Drive continuous improvement and error correction (Grabowski et al., 2007).	Great introspection practice for continuous learning organization (Oswald, 2020).
	Measuring success ("*things going right*") enables recognition and encouragement of workers' good safety practices (Hinze et al., 2013; Sheehan et al., 2016).	Sophisticated analysis methods have a potential to identify systemic vulnerabilities and to detect accident precursors (Hallowell et al., 2020).
Disadvantages	Ambiguity around leading indicator's definition, application and functions impedes its adoption by companies (Kenan & Kadri, 2014; Guo & Yiu, 2016).	Recording of lagging indicators becomes distorted from the actual events, when used as a benchmarking criterium (Costin et al., 2019; Floyd, 2021).
	Elements of leading indicators are unique and identified leading indicators are not readily generalizable to other organizations or projects (Xu et al., 2021).	Past mistakes and accidents are mostly non-generalizable for future construction projects (Elsebaei et al., 2020; Floyd, 2021).
	Sole quantification-based safety performance indicators (leading and lagging indicators) fail to holistically indicate a safety performance (Oswald, 2020).	
	Recording and analyzing only high severity and high frequency occurrences and ignoring seemingly statistically insignificant data obstructs the learning opportunity (Hopkins, 2009; Floyd, 2021).	
	The emergent nature of most leading indicators that are only discernible in the operation stage of projects makes the process of knowledge transfer (and adoption of developed leading indicators) difficult (Haas & Yorio, 2016).	Outcomes of analyzing (lagging indicators) based on basic analysis methods are invalid to identify systemic failures or to have predictability (Hughes & Ferrett, 2020). Whereas, sophisticated analysis methods (of lagging indicators) are not affordable and widely adopted and only statistically significant events can be analyzed in sophisticated analysis methods, hence there is a lack of empirical studies proving such methods' credibility (Erkal et al., 2021).

sification types; and (3) development methodologies. Therefore, Table 3 describes a compilation of leading indicators' definitions (arranged from early to recent years) and Table 4 expands upon the classification types of leading indicators identified through content analysis of extant literature.

The definitions of leading indicators included in Table 3 are arranged in chronological order from the earliest to the most recent to show their development in safety science. Moreover, a 'semantics' column was added to reveal how the definition (and understanding) of leading indicators has evolved over time. The definitions starting from 1999 to 2012 describe leading indicators as an outcome, *viz.,* indicator of events that has occurred (alongside the description as precursors, *viz.*, indicators predicting events that are going to occur). However, the outcome is defined as the main

Table 3
Etymology of leading indicator.

Definitions	Citation	Semantics
A safety indicator is a statistic or other unit of information that reflects directly or indirectly the extent to which an anticipated outcome is achieved or the quality of the processes leading to that outcome.	NOHSC, 1999 (cited in Guo & Yiu, 2016)	Outcomes; Precursors; Measurement of positive events; Assessment of safety management systems
Leading indicators provide information about developing or changing conditions and factors that tend to influence future human performance.	EPRI, 2000 (cited in Jazayeri & Dadi, 2017)	Precursors; Measurement of positive and negative events
Measurements linked to preventive or proactive actions.	Toellner, 2001 (cited in Xu et al., 2021)	Precursors;
A safety indicator is a measurable/operational variable that can be used to describe the condition of a broader phenomenon or aspect of reality.	Øien, 2001b (cited in Guo & Yiu, 2016)	Measurement of positive and negative events;
The leading indicator identifies failings or 'holes' in vital aspects of the risk control system discovered during routine checks on the operation of a critical activity within the risk control system.	Health, and Safety Executive (HSE), 2006	Measurement of negative events;
Leading indicators are conditions, events, or measures that precede an undesirable event and that have some value in predicting the arrival of the event, whether an accident, incident, near miss, or undesirable safety state.	Grabowski et al., 2007	Precursors; Measurement of negative events;
A safety performance indicator is a means for measuring the changes in safety level over time resulting from actions taken.	OECD, 2008	Outcomes; Measurement of positive and negative events;
An indicator that changes before the actual risk level of the organization has changed.	Kjellén, 2009	Precursors;
Leading indicators are proactive measures of performance before any unwanted outcomes have taken place.	Dyreborg, 2009	Precursors; Measurement of and negative events;
A safety indicator is a proxy measurement for items identified as important in the underlying model(s) of safety.	Wreathall, 2009	Assessment of safety management systems
An indicator should measure the state of the safety management system.	Hopkins, 2009	Assessment of safety management systems
Safety indicators are measures of the effectiveness of safety management tasks.	Cipolla et al., 2009 (cited in Guo & Yiu, 2016)	Assessment of safety management systems
Lead safety indicators indicate either the current state or the development of key organizational functions, processes and the technical infrastructure of the system.	Reiman & Pietikäinen, 2012	Precursors; Outcomes; Assessment of safety management systems
Positive performance indicators that address health and safety climate.	Agumba & Haupt, 2012	Outcomes; Measurement of positive events;
Leading indicators of safety performance consist of a set of selected measures that describe the level of effectiveness of the safety process.	Hinze et al., 2013	Assessment of safety management systems
Proactive and predictive measurements that enable safety condition monitoring, which reduces the need to wait for the system to fail to identify weaknesses and to take remedial action.	Eaton et al., 2013	Precursors; Assessment of safety;
Indicators that enable anticipation of performance evaluation are called leading indicators.	dos Santos Grecco et al., 2014	Precursors;
Leading indicators are safety-related practices or observations that can be measured during the construction phase, which can trigger positive responses.	Hallowell et al., 2013	Assessment of safety management systems; Measurement of positive events;
Characteristics that foment safety behavior, such as safety culture or safety climate.	Navarro et al., 2013	Assessment of safety and safety culture;
Something that provides information that helps the user respond to changing circumstances and take actions to achieve desired outcomes or avoid unwanted outcomes.	Step-Change in Safety, 2014 (cited in Guo & Yiu, 2016)	Precursors; Measurement of negative and positive events
A set of quantitative and/or qualitative measurements that can describe and monitor validly and reliably the safety conditions of a construction project.	Guo & Yiu, 2016	Assessment of safety
Precursors to harm that provide early warning signs of potential failure.	Shea et al., 2016 (cited in Xu et al., 2021)	Precursors; Measurement of negative events;
Safety leading indicators are proactive, pre-incident measurements consisting of multiple levels of safety protections carried out before the start of (or during) the construction phase, at both the organization and project levels.	Karakhan et al., 2018 (cited in Xu et al., 2021)	Precursors; Assessment of safety management systems;
Safety leading indicators are measures of the safety management system that correlate with injury rate.	Alruqi & Hallowell, 2019	Measurement negative events; Assessment of safety management systems;
Forewarns the analyst about potentially different actions to be undertaken in order to grasp an opportunity or to evade a threat.	Patriarca et al., 2019	Precursors; Measurement of negative and positive events;
The quantity of safety management activities performed to prevent injuries	Hallowell et al., 2020	Assessment of safety management system;
Leading indicators show the activities of an organization regarding the prediction and prevention of accidents before they occur.	Falahati et al., 2020	Precursors; Assessment of safety management systems;
Leading indicator are safety measurement which provide a future forecast of the safety performance based on the activities and practices implemented not incidents. So, it is proactive measure to what might happen in the future.	Elsebaei et al., 2020	Precursors; Assessment of safety management systems;
Safety leading indicators are measures that indicate the current performance of a safety management system of a project or firm. They can: (1) identify the system's weaknesses and strengths, (2) identify situations that might cause incidents and injuries, and (3) drive proactive actions to prevent an incident or injury before it occurs and achieve continuous improvement.	Xu et al., 2021	Precursors; Assessment of safety management systems; Measurement of positive and negative events;

Table 4
Typologies of leading indicators.

Types of leading indicators		Definition
Classification based on the length of time leading indicator takes to measure and respond to observed event	Passive	Passive indicators are those that cannot be altered in a short period of time (Jazayeri & Dadi, 2017). Measurements or information streams that provide an indication of the probable safety performance to be realized within a firm or on a project. They are predictive on a macro scale but have limited predictive value after a certain point in time or once a threshold is reached (Costin et al., 2019). An indication of the probable safety performance to be realized within a firm or on a project. The process being monitored by passive leading indicators cannot generally be altered in a short period of time. Passive leading indicators can be used to predict, on a larger or long-term basis, the likely safety performance to be realized by a company or on a particular project (Hinze et al., 2013). Indicators that take a long time to measure (Falahati et al., 2020). Indicators that are typically implemented before work begins and remain relatively static once a project has begun (Alruqi & Hallowell, 2019).
	Active	Indicators that can be readily changed during the construction phase - they measure quality of implementation (Alruqi & Hallowell, 2019). Measurements or information streams that provide an indication of the probable safety performance to be realized within a firm or on a project. They are dynamic and thus, more subject to change in a short period of time. ALIs may be characterized as the "pulse" of the construction project in terms of daily safety behaviors and practices (Costin et al., 2019). Indicators that can be measured within a shorter period (Falahati et al., 2020). Active leading indicators are those which are more subject to change in a short period of time (Hinze et al., 2013). Active indicators are those that can be subject to change in a short period (Jazayeri & Dadi, 2017).
Classification based on the target of measurement	Structural	Show the status of safety management systems, including policies, objectives and plans, procedures, and guidelines (Falahati et al., 2020). Indicators being applied for the evaluation of system compliance with a given specification. They measure whether individual components of the system are properly designed or evaluating the extent to which system procedures are implemented and being followed in the enterprise (Podgórski, 2015). The formal description of all the efforts that are made by the company into managing health and safety at the workplace (Cambon et al., 2006).
	Operational	Evaluate the effectiveness of the internal processes of safety and health management systems (Falahati et al., 2020). Indicators that provide information on the status of individual processes within the management system. Such indicators provide information on progress of change within the management system and assist in forecasting future status and planning (Podgórski, 2015). The level of integration and of influence of formal processes on the practices and the working environment of people (Cambon et al., 2006).
Classification based on the target of measurement	Safety management system indicators	Indicators that measure individual safety practices and activities, providing information about safety management system implementation and thus directing remedial actions (Guo and Yiu, 2016).
	Indicators of abstract safety constructs	Indicators that measure safety constructs such as management commitment, safety motivation or social support. Collecting information about abstract safety constructs often requires qualitative interviews and surveys (Guo and Yiu, 2016).
Classification based on function of measurement	Leading monitor indicators	Indicators of organizational potential to achieve safety. They do not directly predict the safety-related outcomes of the sociotechnical system since these are also affected by numerous other factors such as external circumstances, situational variables and chance (Reiman & Pietikäinen, 2012). Monitor indicators reflect the potential and ability of a given organization to operate safely (Podgórski, 2015).
	Leading drive indicators	Indicate development activities aiming at improving safety (Reiman and Pietikäinen, 2012). Drive indicators allow the measurement of the degree of execution of selected actions in priority areas of the management system, such as leadership, competence management, hazard control, change management, etc (Podgórski, 2015).
Classification based on severity of observed event	Tier 3 leading indicators	An actual event or discovery of a potentially unsafe situation, e.g., near miss. They are failure of process safety management systems that give an excellent road map to what part needs to be strengthened (Kenan & Kadri, 2014). Represents events involving challenges to safety systems, such as safe operating limit excursions, inspections of primary containment outside acceptable limits, etc (Murray, 2015). Events that are considered to be a challenge to a safety management system that exceed Safe Operating Limits (SOL) (Stauffer & Chastain-Knight, 2021).
	Tier 4 leading indicators	Indicators that monitor the health of important aspects of the process safety management system which give early indication of deterioration in the effectiveness of key safety system and enable remedial action to be undertaken to restore the effectiveness of these key barriers, before any loss of containment event takes place (Kenan & Kadri, 2014). Indicators that categorize operating discipline and management system performance (Murray, 2015).

Table 4 (*continued*)

Types of leading indicators		Definition
Classification based on the target of measurement	Predictive proactive indicators	Predictive proactive indicators supply information on the types of managerial actions that have been taken to reduce workplace risk (Haas & Yorio, 2016).
	Monitoring proactive indicators	Monitoring proactive indicators include health and safety related outcomes observed prior to the occurrence of a major incident such as small releases of hazardous substances or near misses, the results of safety inspections and behavioral observations, the results of safety audits, and safety attitudes (Haas & Yorio, 2016).

feature of lagging indicators according to the Bowtie diagram (Swuste et al., 2016). These early formative descriptions of leading indicators as 'outcomes' and/or 'precursors' represent some examples of leading indicators that are simultaneously lagging and leading (Lingard et al., 2017). However, post 2012 and until recent years, this description changes to precursors only, which signifies the increasing focus on the main function of leading indicators as antecedents. Table 3 is supplemented with Fig. 2, which combines bar chart and word cloud illustration of the words in the 'definition' and semantics' columns (of Table 3). The bar chart demonstrates the frequency of the terms used to define leading indicators in descending order, while the word cloud illustrates them (*i.e.*, frequency of words to describe leading indicators) by the their size (e.g., larger sized words have higher occurrence to describe leading indicators).

Apart from the keywords themselves (*viz.*, '*safety*,' '*leading*,' '*indicators*'), the terms such as '*precursors*' ($f = 17$), '*proactive*' ($f = 6$), '*outcomes*' ($f = 9$), '*negative*' ($f = 11$), '*positive*' ($f = 11$), '*measure/ment*' ($f = 28$) and '*assessment*' ($f = 16$) are the most frequent words used to describe leading indicators. Contrary to lagging indi-

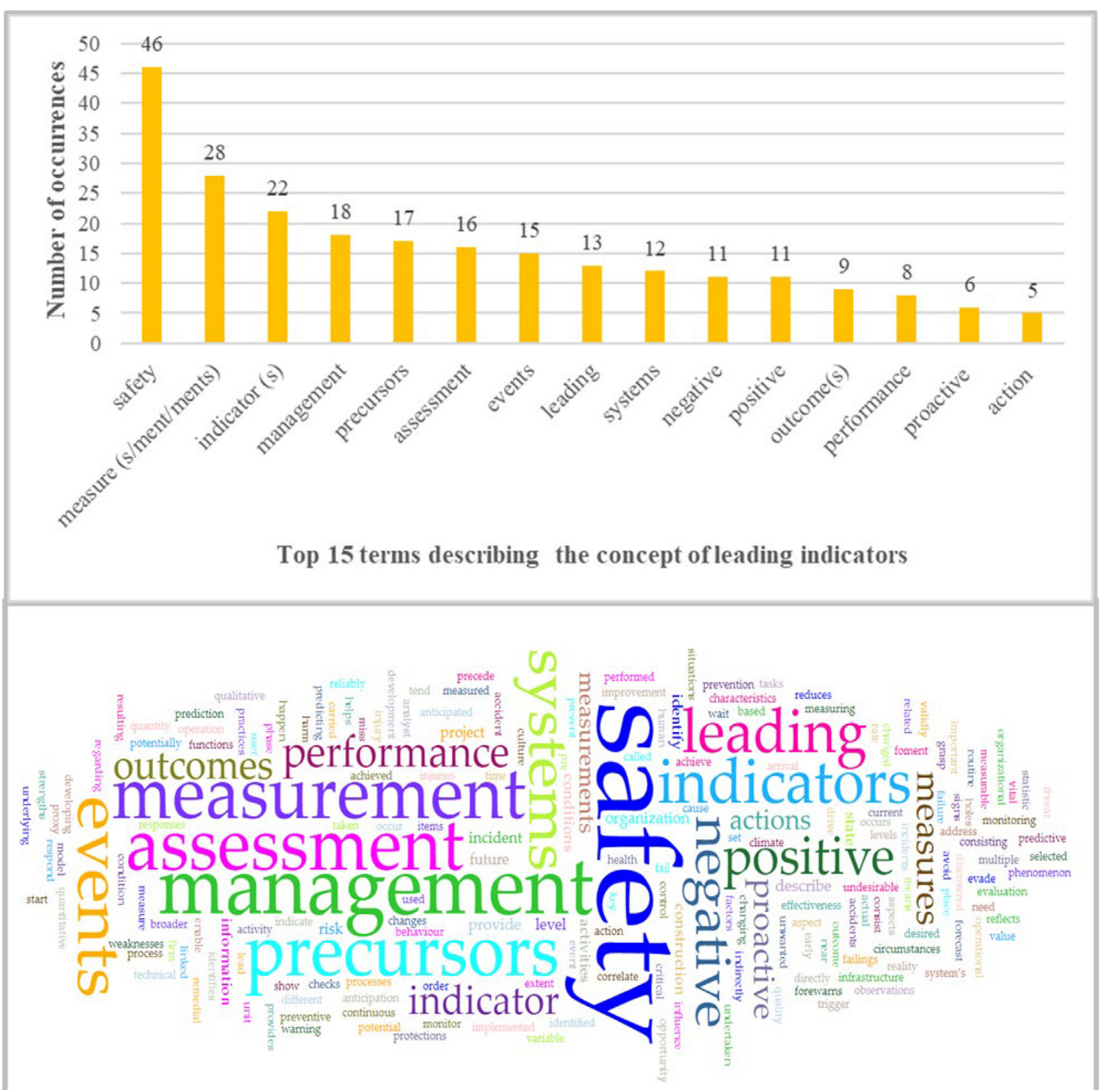

Fig. 2. Frequency of occurrence and word cloud depiction of terms defining leading indicators.

cators that measure negative events, leading indicators are defined to measure both negative and positive events - a feature that is pivotal for recognition of positive events and learning from success (Patriarca et al., 2019; Reiman & Pietikäinen, 2012). Therefore, the terms '*negative*,' '*positive*,' and '*events*' are frequently occurring words in the word cloud depiction. Regarding the target these indicators are measuring, there is a contrasting division between *safety management systems* on one side and *safety, safety culture* on the other side. This ambiguity around what is the target of leading indicators' measurement can be elucidated upon by the different types of leading indicators described in Table 4. This table presents six dichotomous clusters of classification (*i.e.*, with two subgroups within each cluster), four out of which are highlighted with light yellow shading. These four classification clusters contain the following leading indicators types: (1) PLIs and ALIs; (2) structural and operational leading indicators; (3) safety management system indicators and indicators of abstract safety constructs; and (4) predictive proactive indicators and monitoring proactive indicators. The first type of each of the four clusters focuses on measuring and monitoring safety management systems, whereas the second type of each cluster is concerned with measuring and monitoring safety and safety culture, respectively.

These dichotomous types of leading indicators (each type with different functions and focuses) create confusion around the nature, function, and application potentials of leading indicators, which also leads to the absence of their unanimous and operationally crisp definition. For example, variations in: definitions (whether they measure safety management systems or safety); time period to measure (whether they measure safety performances occurring in the long time or short time period); and function they fulfil (whether they are used only for measuring recording and learning or for monitoring and timely correcting), are respectively associated with PLIs and ALIs types. Therefore, it is crucially important to differentiate the two types of leading indicators. Namely, PLIs (similarly, structural leading indicators, safety management system indicators, and predictive proactive indicators) focus on monitoring and measuring safety in terms of adopted organizational safety management systems over an extended timeframe to correct and obtain feedback. Therefore, PLIs fulfil the function of measuring, recording, and learning, since obtaining feedback from adopted and implemented safety management systems policies, processes, plans, and guidelines requires long time period. On the other hand, ALIs (similarly, operational leading indicators, indicators of abstract safety constructs, and monitoring proactive indicators) are focused to monitor and measure an organization's safety and safety culture in the operation stage, which provides real time feedback of current safety status. ALIs serve the function of monitoring safety in real time and timely correcting issues arising in case an undesired event occurs. Leading indicators described within the literature predominantly bear the features (i.e., function and nature) of PLIs, but are rarely associated with the function and nature of ALIs.

The last construct of leading indicators is the methodologies used to develop them. Content analysis revealed prominent studies that develop and identify leading indicators using various methodologies (such as Delphi method; Erkal et al., 2021); Cross-sectional analysis (Manjourides & Dennerlein, 2019); and Analytical Network Process (ANP) (Ebrahimi et al., 2021)). Table 5 identifies that only 17 (*i.e.*, 18.28 %) out of 93 studies (*i.e.*, publications selected for this study) focus on developing leading indicators using various methodologies.

The source of materials used for developing and identifying leading indicators ranges from pertinent scientific literature to industry standards and survey responses. The most frequently used data source is '*past accident records*' *viz.*, lagging indicators. Eight of these 17 studies used organizations' past accident records to identify company-specific leading indicators. The next frequently used material source is '*pertinent literature*' ($f = 4$), followed by '*industry specific white papers and recommendations*' ($f = 3$) and '*survey responses*' ($f = 2$).

All developed leading indicators from each study (described in the third column of Table 5) were reviewed to identify which element of the sociotechnical systems and projects (such as human, machinery, site, or procedures) they represent. Most of the developed leading indicators ($f = 12$) refer to the '*human*' aspect of sociotechnical systems, followed by '*procedures*' ($f = 7$). The most common methodology used to develop, identify, or select leading indicators from a given source of materials is based on surveying opinions ($f = 4$) by congregating or ranking survey responses, through either the Delphi method or Focus groups method; followed by multi-criteria decision making (MCDA) methods (or multi-criteria decision analysis (MCDM) methods) ($f = 3$) such as the Analytic Hierarchy Process (AHP), Decision-Making Trial and Evaluation Laboratory (DEMATEL) or Analytical Network Process (ANP). This observation identifies that the methodologies for leading indicators' development predominantly rely on subjectivity and/or opinion or interpretation-based approach. However, such an approach must be combined with testing and revision in pilot or case studies to develop the most appropriate leading indicators for a specific organization and remain open to adjustments even after their adoption.

5. Discussion

The results of cross-componential analysis identify the main features of both leading and lagging indicators - both of which have inherent (and dissimilar) pros and cons, barriers, and misinterpretation of their purpose, function, and application (in Table 2). Lagging indicators constitute a mainstream measurement of safety, widely adopted by many safety–critical organizations in various industry. Yet, the function and purpose of using lagging indicators have been distorted from serving altruistic learning purposes to being recklessly promoted as one of the predominant success criteria of companies (Oswald, 2020). Where lagging indicators are recorded comprehensively for the purpose of learning and understanding the complex interaction of system elements and contextual factors in complex sociotechnical systems, they can uncover mistakes, early signs, and gaps in the safety management systems. Moreover, they can augment the development of precursors of undesirable events, namely leading indicators (Elsebaei et al., 2020).

5.1. New theory development

The process of developing leading indicators from past safety performance records is depicted in a new theoretical conceptual model presented in Fig. 3, which is premised upon the rich synthesis of literature previously analyzed. The model proceeds with differentiation between the application of PLIs (long double-sided arrow on the left side of the model) and ALIs (short double-sided arrow on the right side of the model). This is followed by the inputs for development (purple line) and application of (light yellow line) PLIs and ALIs down across the model. PLIs application is depicted as a long arrow ('Measurement of performances requiring long time period'), since PLIs measure the efficiency of organizations' safety management systems. This takes a longer time period to obtain feedback and to adjust safety management systems (where correction is required). For example, training courses implemented (which is part of organizations' safety management systems) requires a longer time period to reveal its efficiency, that is, the competency level of employees is revealed long after the comple-

Table 5
Methodologies used for leading indicators development and identification.

Methods used to develop leading indicators	Source being analyzed (LI are developed from)	Developed/ identified leading indicators	Citation	Element/ aspect of system
Analytic Hierarchy Process (AHP)	Pertinent literature and normative documents on OSH MS (ILO-OSH 2001, OHSAS 18001).	20 leading indicators (Key performance indicators)	Podgórski, 2015	Human; Procedures.
AHP and Bayesian network	OHSAS 18001: 2007 management system components; and ongoing construction project operations.	19 structural, 27 operational and 33 active leading indictors	Falahati et al., 2020	Human; Machinery; Sites.
Functional Resonance Analysis Method (FRAM)	Ongoing construction project (difference between WAP and WAD).	Not specified	Costantino et al., 2020	Not available.
Selection by research team of experts	Triangulation of case studies, project descriptions of safety award–winning projects, and expert brainstorming.	13 passive leading indicators	Hallowell et al., 2013	Human.
Review of the literature	Pertinent literature (18 articles).	15 leading indicators	Neamat, 2019	Human.
Content analysis and Natural language processing (NLP)	Accident investigation reports.	11 leading indicators (upstream precursors)	Shrestha et al., 2020	Human; Machinery; Sites.
Ranking survey answers	Hazard factors identified by Centre for Chemical Process Safety.	10 leading indicators	Baek et al., 2018	Human.
Hybrid method consisting of Delphi method and Focus groups	Data obtained from structured brainstorming of selected experts in focus group study.	41 leading indicators	Erkal et al., 2021	Human; Procedures; Sites.
Authors' conceptual model (based on two Rasmussen's safety models: the model of migration and the sociotechnical system view (STS))	Pertinent literature and Hypothetical project.	32 leading indicators	Guo & Yiu, 2016	Human.
Machine learning	Records of project performance and safety-related data.	Not specified	Jafari et al., 2019	Not available.
Machine learning	Seven years period data of project performance and safety-related records (i.e., monthly inspection records, accident cases, monthly project-related data).	Not specified	Poh et al., 2018	Not available.
Survey of Centre for Chemical Process Safety (CCPS) members	Responds from survey.	23 leading indicators	Kenan & Kadri, 2014	Human; Machinery; Procedures.
Cross sectional analysis	Recordable cases (RC) and days away restricted or transferred (DART).	6 passive leading indicators	Manjourides & Dennerlein, 2019	Procedures.
Ranking through fuzzy model based on experts opinion and Pareto principle	Health and Safety documents (i.e., industry white papers, standards, recommendation and guidance publications) and reports of major accident analysis.	44 leading indicators	Santos et al., 2019	Human; Machinery; Procedures; Sites
Systematic literature review	32 pertinent articles.	16 leading indicators	Xu et al., 2021	Human; Sites; Procedures.
Longitudinal Logistic Regression and Longitudinal Count Regression models	Safety records of 2006–2017 years from Mine Safety and Health Administration (MSHA) database.	3 leading indicators	Yorio et al., 2020	Procedures.
Human Factors Analysis and Classification System (HFACS) approach (to identify human factor) followed by Decision- Making Trial and Evaluation Laboratory (DEMATEL) method and the Analytical Network Process (ANP)	42 safety records of 2007–2018 years from Transportation Safety Board of Canada.	3 leading indicators	Ebrahimi et al., 2021	Human.

tion of training courses (in the operation stage). If the competency level is deemed to be inadequate, similarly a longer time period would be required to correct and adjust the training courses. However, ALIs application is illustrated as a shorter arrow ('Measurement of performances requiring short time period') to convey the shorter time period ALIs take to measure safety and safety culture.

Because the study concludes that the list of leading indicators to be adopted for every organization is unique and distinctive, lagging indicators are regarded as the most appropriate and evidence-based source of material for both leading indicators developments (*i.e.*, PLIs and ALIs). This introspective practice of deducing knowledge from past events (annotated with a white circled letter 'a') is a *terminus a quo* to understand and identify leading indicators that are most relevant to a specific company. Knowledge gained through analyzing lagging indicators allows generation of company-specific leading indicators that are predominantly of a negative nature, such as the measurement of undesirable outcomes (*i.e.*, accident occurrences that reveal gaps, failures, and mistakes in organizational safety management systems) that organizations are planning to avoid. Therefore, the insights and conclusion reached from analysis of lagging indicators must be combined with industry standard documents and latest guidance notes (annotated with a white circled letter 'b'), which enables generation of (positive) expected performance metrics. The mixture of knowledge about conditions to avoid that are observed from lagging indicators (annotated with red half-circular arrow i)

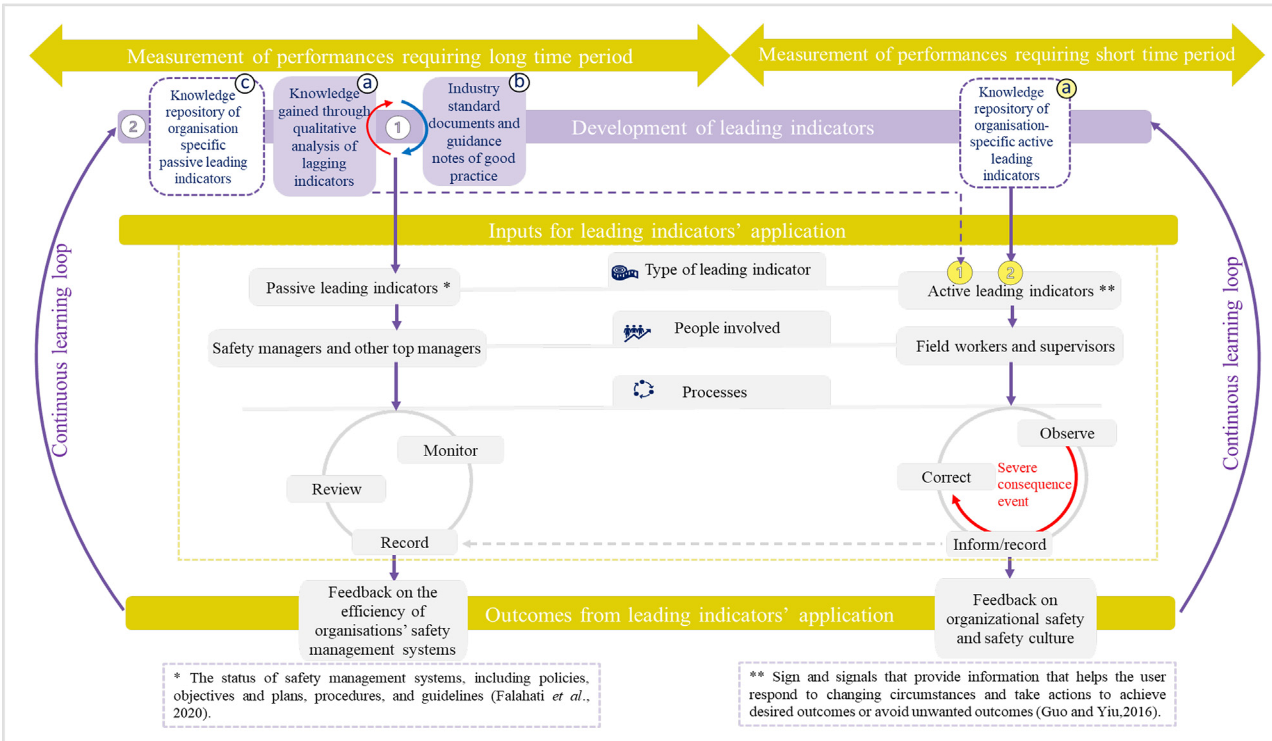

Fig. 3. Conceptual model of leading indicators development and application process for continuous learning organizations.

and normative or desired outcome metrics emerged from industry standard papers (annotated with a blue half-circular arrow), sets the foundation of initial PLIs' development (annotated with white circled number '1′ on the left side of the model).

Analyzing lagging indicators and learning about organizational safety potentials from industry guidance papers helps to identify a large majority of PLIs (e.g., competency or incompetency of workers, *viz.*, quality and efficiency of organization's training programs), which can be fed forward for application (left side of input element) as a first input. The second element of the input is people involved in the application of PLIs, followed by the third element, processes they need to adopt for application. Safety managers and other top managers (who are key decision-makers in company's safety management systems) are the people responsible for PLIs' application by using a cyclical process of monitor-record-review. As a result, application of PLIs generates the outcome (left side of outcome block in the model) of negative or positive measurement, that is, feedback on the organizations' safety management systems (and thus, also serves the functions of recording, assessing, reviewing and learning). The generated outcomes from PLIs' application render a new knowledge for developing and reviewing the existing PLIs (annotated with a white circled number '2′). Therefore, the second round of development or revision process of PLIs after the first-time application will involve three sources, *viz.:* (1) knowledge gained through analysis of lagging indicator (annotated with white circled letter 'a'); (2) industry standard documents and guidance noted of good practice (annotated with a white circled letter 'b'); and (3) knowledge repository of organization specific passive leading indicators (annotated with a white circled letter 'c'). Consequently, these steps of development and application of PLIs engenders an infinite loop of continuous learning by measuring and adjusting already adopted PLIs based on feedback obtained from a previous application(s).

Similarly, short time application (right side of the model) proceeds with identification of ALIs in the development stage and forwarding them for application as the first element of input. Subsequently, fieldworkers and supervisors (as the second element of input) adopt the cyclical process of observe-inform/record-correct (as the third element of input). This, in turn, creates the outcome of feedback (positive or negative) for safety and safety culture through ALIs functions of monitoring, responding, and learning. Similar to PLIs application, the outcome from ALIs application (*i.e.*, feedback on organizational safety and safety culture) generates novel insight for an organization's knowledge repository that contains organization-specific ALIs (annotated with a yellow circled letter 'a' on the model's right side). However, there are two main differences in the process of development and application of ALIs and PLIs. The first contrast to PLIs development is that ALIs development occurs in the process of application because it is an emergent leading indicator. Nonetheless, initial insights as to how to identify ALIs can be obtained from existing lagging indicators of that company (arrow heading to a yellow circled number '1′ on the right side of the model). Therefore, due to their emergent nature of ALIs, the model adopts the definition of ALIs as signs and signals that provide information to support users to respond to changing circumstances and take corrective actions to achieve desired outcomes or avoid unwanted outcomes (Guo & Yiu, 2016).

The second difference is in the process element of ALIs' application, where depending on the observed event, different steps might be taken. In case of a positive event being observed (*viz.* success), the event must be recorded in the safety management system for recognition (arrow heading from 'inform/record' step of ALIs' application side to 'record' step on the PLIs' application side). In such instance, ALIs serve the function of learning (from success), alongside the service of monitoring safety in real time. Conversely, a negative occurrence of different severity and emergency level might require immediate action of correction (red arrow on processes element of ALIs application), followed by observation of that correction and then the recording step. Alternatively, if the observer decides (to their best knowledge at that moment) that the negative occurrence has minor consequences and requires a team to correct it, then the observer must inform the workers who will be impacted by the action and then correct, observe, and record the incident/event.

This model of developing and implementing leading indicators attempts to change the common approach of trying to fit work-as-done (WAD) to work-as-planned (WAP), towards adapting the WAP based on the conditions and circumstances of work being performed. Since the condition and circumstances of sociotechnical systems (*i.e.*, construction projects) are dynamic and volatile, only guidance and feedback obtained through leading indicators can reveal the changing nature of the work environment and complex interaction of system elements (human, machinery and site). The model provides a signpost to what can be achieved through diligent collection of data by observing the complex and tightly coupled work environment; but without application and empirical studies, the model remains as a mere blueprint. Therefore, the model's development achieved through inductive reasoning (and premised upon pertinent literature) requires deductive application and validation using real-life case studies (as opposed to perceptual type studies implemented). Future empirical studies based on this model will intrinsically generate more knowledge about ALIs – *per se*, an area recognized to have a notable dearth in current literature.

Limitations of the study must also be noted, namely, the keyword search terms upon which the model is derived was limited to very specific terminologies used (*viz.* "leading indicators" and "safety management"). It could be argued that a broader search of literature (encompassing a wider range of keyword terms) could have introduced further perspectives into the theory build presented in this current research. Conversely, such an approach could also have diluted the research outputs (namely, new theory presented) reported upon. The choice of keywords is a notable limitation of the interpretivist philosophy because it is premised upon the individual researcher's subjective perspective and possible bias – a limitation widely acknowledged within literature (cf. Roberts & Edwards, 2022). This limitation must, however, be balanced with the advantage of generating new theory based upon existing published research that has already been validated (via a robust peer review process). Hence, the interpretivist approach is often more reliable and trustworthy than other philosophical stances (cf. Dudovskiy, 2018).

6. Conclusion

Construction accidents and injuries continue unabated across the globe despite the historic and considerable investment in research, training, technological, and legislative developments. To reverse the direction of this well-trod chartered path, a new modus operandi is needed to generate fresh insight and engender wider polemic debate. The work presented in this paper acts as a catalyst for that change and signposts much-needed new direction for future research.

6.1. Theoretical contribution of the study

Compilation and deduction of leading indicators' constructs (*i. e.*, definition, classification and development methods) from extant literature adds a valuable theoretical contribution to advancing the wider body of knowledge on leading indicators. The study concludes that inconsistency in leading indicators' definitions and functions are related to the difference between two types of leading indicators, namely passive leading indicators (PLIs) and active leading indicators (ALIs). PLIs measure and assess the elements of organizational safety management systems (e.g., the efficiency of training programs or contractor selection methods, impact of adopted preventative steps or designed work process). Whereas ALIs measure or unravel granular and dynamic elements of safety, such as preventable and correctable early signs of possible negative or positive events that arise from ongoing operations and decision makings. Therefore, focusing on ALIs as a proactive safety management serves as a gauge for ever-changing/fluctuating and unpredictable status of safety and risk in complex sociotechnical type workplaces. However, ALIs studies remain strikingly scant - only 4 out of 93 publications (included for this study) focus on this type of leading indicators. Given the capacity of ALIs to generate knowledge and immediate feedback from the action being performed in the operation stage (which allows close to real-time monitoring of safety or unsafety), more studies on their theoretical and practical applications are needed.

6.2. Practical contribution of the study

As a practical contribution, the conceptual model guides adopters of leading indicators how to differentiate the types of leading indicators (*viz.*, passive leading indicators and active leading indicators) and informs the process of developing, adopting, and implementing the two types of leading indicators. Consequently, the infinite loop of development and application of leading indicators, which encourages continuous learning of organizations (introduced in the model), will be invaluable for adopters to generate their own knowledge repository of leading indicators and to continuously learn and improve their safety and safety performance.

In terms of applying the conceptual model offered by this study, there are number of considerations that organizations must include to effectively adopt leading indicators as their safety performance measurement. Although an organization's lagging indicators and industry white papers are important sources (and constitute the starting point to develop leading indicators), a pivotal step prior to that is to comprehensively understand the main features of leading indicators by their definition, function, focus, and types. Without this knowledge, efficiency of developed leading indicators will remain questionable (regardless of the source of materials used to develop them) and hence, understanding the constructs of leading indicators is a first priority for adopting organizations.

The next priority for companies adopting leading indicators must be to improve recordings of lagging indicators. Since lagging indicators are a crucial source of knowledge for the development of organization-specific leading indicators, the efficiency and accuracy of these are determined by the accuracy and quality of lagging indicators' recordings. Furthermore, it must be highlighted that leading indicators are not an absolute measure of safety, but rather an indicative and guiding signal with which safety, safety culture, and safety performance of organizations can be monitored. Therefore, for a comprehensive observation, the development of leading indicators must encompass different elements of complex sociotechnical systems (*viz.* workers, machinery and sites) on different levels (organizational and procedural level), since accident(s) occurrence is the result of multiple sources of factors that are unpredictable and emergent.

Another caveat for efficient adoption of leading indicators is to measure them qualitatively as well as quantitatively in order to capture the breadth and depth of information. Instead of merely measuring frequency of positive or negative occurrences, the focus must be on observed elements/events themselves through continuous monitoring and anticipation by frontline workers.

Lastly, the knowledge about leading indicators' (particularly ALIs) constructs must be efficiently conveyed to frontline workers (through hands-on training and practices) because they are the stakeholders who are exposed to real challenges of changing work environment. Therefore, frontline workers play an important role in: observing the changing signs and signals; 'reading' those leading indicators in the work environment; and acting in a timely manner to correct unsafe observations or acknowledging and recording positive occurrences. The knowledge about leading indicators can be introduced on routine check sessions, by involving frontline workers in the process of detecting leading indicators. New theory development is the basis upon which progress is made. Hence, the importance of the present study in challenging existing knowledge and suggesting alternative approaches to enhance safety (to mitigate accidents) within society.

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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Cue utilization and pool lifeguarding

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ABSTRACT

Introduction: Amongst pool lifeguards, the capacity to identify drowning swimmers quickly and accurately depends on the interpretation of critical cues. However, assessing the capacity for cue utilization amongst lifeguards at present is costly, time-consuming, and largely subjective. The aim of this study was to test the relationship between cue utilization and the detection of drowning swimmers in a series of virtual public swimming pool scenarios. *Method:* Eighty-seven participants with or without lifeguarding experience engaged in three virtual scenarios, two of which were target scenarios where drowning events occurred within a 13 minute or 23 minute period of watch. Cue utilization was assessed using the pool lifeguarding edition of the EXPERTise 2.0 software following which 23 participants were classified with higher cue utilization, while the remaining participants were classified with lower cue utilization. *Results:* The results revealed that participants with higher cue utilization were more likely to have acquired experience as a lifeguard, were more likely to detect the drowning swimmer within a three minute period, and, in the case of the 13 minute scenario, recorded a greater dwell time on the drowning victim prior to the drowning event. *Conclusion:* The results suggest that cue utilization is associated with drowning detection performance in a simulated environment and could be employed as a basis for assessments of performance amongst lifeguards in the future. *Practical Implications:* Measures of cue utilization are associated with the timely detection of drowning victims in virtual pool lifeguarding scenarios. Employers and trainers of lifeguards can potentially augment existing lifeguarding assessment programs to quickly and cost-effectively identify the capabilities of lifeguards. This is especially useful for new lifeguards or where pool lifeguarding is a seasonal activity that might be associated with skill decay.

1. Introduction

Lifeguarding is a critical risk control that is intended to safeguard swimmers. The primary role of lifeguards is to identify, as quickly and as accurately as possible, situations where swimmers are at risk of drowning (Schwebel, Lindsay, & Simpson, 2007). However, the capacity to identify swimmers at risk is often impeded by a range of factors, including the lack of pre-existing knowledge of swimmers' skills and abilities, local weather conditions, distractions from other patrons or colleagues, visual obstructions, and/or the requirement to sustain attention over an extended period (Schwebel, Simpson, & Lindsay, 2007). Therefore, detecting struggling swimmers depends on the capacity of the lifeguard to extract, from a complex scene, critical cues that may emerge quickly and spontaneously during a period of watch.

The capacity to extract and make sense of critical cues in a visual scene requires a comparative assessment against cues that lie resident in memory. Capitalizing on production memory, cues constitute feature-event relationships where the emergence or absence of a feature quickly and nonconsciously draws attention to an event, thereby enabling the opportunity for meaning and creating the opportunity for timely interventions (Wiggins, 2021; Wiggins, Griffin, & Brouwers, 2019). For example, an experienced lifeguard might associate a young, unaccompanied child playing near the edge of a pool as a prelude to a drowning event where the child falls into the pool inadvertently, becomes disoriented, and panics, leading to water ingestion (Harrell & Boisvert, 2003).

The number and level of sophistication of cues acquired by lifeguards increases the likelihood that the precursors of drowning events are recognized and early interventions can be initiated (Gomes, Young, & Hon, 2022). However, the repertoire of cues available to lifeguards is difficult to establish at any point in time and is typically inferred on the basis of training and experience, rather than tested explicitly (Page, Bates, Long, Dawes, & Tipton, 2011). Where testing does occur, it often involves one-off simula-

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tions using low fidelity tools such as manikins that fail to capture the nuanced features that are likely to precede drowning events (Vignac, Lebihain, Guignard, Heutte, Le Minor, & Soulé, 2022).

Since cue-based associations are non-conscious, it is also difficult for practitioners to articulate their capacity to utilize cues within a specific context (Cope, Bezemer, Kneebone, & Lingard, 2015). Cues are also idiosyncratic, so that the cues acquired and utilized by one practitioner may be quite different to those used by another, despite the fact that their application may yield similar outcomes in practice (Jung, Vissa, & Pich, 2017). Therefore, comparative analyses of cue utilization are problematic if there is a reliance on a universal set of cues against which to assess their accuracy and effectiveness. An alternative approach involves assessing behavior in response to situations that require the application of cue-based associations and, thereby, infer the capacity for cue utilization.

Behavior-based assessments of cue utilization need to be undertaken from a range of perspectives, since the application of cues involves more than simply generating an accurate response, and differences in exposure may lead to different capabilities. For example, higher levels of cue utilization may also be associated with more rapid responses to cues, a greater capacity to discriminate relevant from less relevant cues, the capacity to prioritize the acquisition of cues in making sense of situation, and the capacity to draw associations between cues that are related.

Referred to as the RAPID approach to the assessment of cue utilization, performance is assessed using five tasks that each comprise a series of domain-related scenarios (Wiggins, 2021). In practice, performance is assessed using norms so that assessments are comparative, rather than absolute. This reflects the fact that the acquisition of cues is associated with exposure to the operational environment and that differences in opportunities to acquire and practice cues will reflect differences in the capacity for cue utilization. For example, a lifeguard who has been working primarily in training pools may have difficulty discriminating signals of distress from vigorous play amongst children that might occur in a recreational pool. Similarly, prioritizing cue acquisition in a recreational pool may be less systematic for a lifeguard who has more familiarity with lap swimmers.

Drawing on the RAPID approach, differences in cue utilization have been associated with differences in diagnostic performance amongst pediatric intensivists (Loveday, Wiggins, Searle, Festa, & Schell, 2013), audiologists (Watkinson, Bristow, Auton, McMahon, & Wiggins, 2018), pathologists (Carrigan, Charlton, Foucar, Wiggins, Georgiou, Palmeri, & Curby, 2021), and radiographers (Carrigan, Magnussen, Georgiou, Curby, Palmeri, & Wiggins, 2021). Higher cue utilization is also associated with fewer programming errors, more frequent peer assessments of expertise amongst software engineers (Loveday, Wiggins, & Searle, 2014), lower cognitive load amongst electricity network operators (Sturman, Wiggins, Auton, Loft, Helton, Westbrook, & Braithwaite, 2019), and a greater frequency of visual saccades amongst drivers (Yuris, Wiggins, Auton, Gaicon, & Sturman, 2019). In combination, these outcomes suggest that, consistent with the theoretical proposition, higher performance is associated with the application of cue-based associations from memory and that this is associated with a reduction in the demands on cognitive resources.

Together with the capacity to quickly and accurately recognize patterns of features, lower cognitive demands during a task have been associated with improvements in sustained attention, since sustained attention is associated with the consumption of cognitive resources (Sturman, Wiggins, Auton, & Helton, 2020). This is especially important in the context of pool lifeguarding where salient features may occur at any time during the period of watch. The aim of the present study was to examine whether different levels of cue utilization in the context of pool lifeguarding are associated with differences in experience as a lifeguard and differences in the accuracy and response latency in detecting drowning victims during a series of a simulated pool lifeguarding scenarios of differing durations.

Simulating drowning scenarios is particularly challenging, since there is a need to capture a wide range of features, many of which are dynamic and are associated with the suspension of disbelief that is necessary to facilitate the level of engagement that corresponds to behavior in the actual environment. Virtual environments potentially offer this immersive context and the capability to represent the complexity of a dynamic scene while enabling observers a degree of agency in determining how they will interact with the scene (Greatbatch & Livingstone, 2018). Together with the capacity to simulate realistic activities, including playing and swimming, it offers an opportunity to situate participants in the context where drowning events are likely to occur. While some aspects of the operational context may be difficult to replicate precisely, it presents a near-to-real representation of pool lifeguarding experience.

The present study comprised three virtual scenarios, two of which involved a passive drowning event. The remaining intervening scenario comprised a foil during which no drowning occurred. Given the role of experience in enabling the acquisition of cues, a positive relationship was hypothesized between cue utilization and experience working as a lifeguard. It was also hypothesized that participants with higher cue utilization would identify, with greater frequency, the drowning victims in the virtual scenarios within three minutes of the drowning event having occurred, record a shorter response latency in detecting drowning victims, and record longer dwell times on victims prior to the drowning event.

2. Method

2.1. Participants

The participants were recruited from lifeguarding and university student populations to ensure a level of variability in the level of exposure and, therefore, the level of cue utilization associated with pool lifeguarding. The sample comprised 87 participants of whom 38 reported at least some experience as a pool lifeguard and 48.3% identified as female, with the remaining 51.7% identifying as male.

2.2. Materials and stimuli

Prior to engaging with the virtual scenarios, the participants were asked to complete the pool lifeguarding edition of EXPERTise 2.0. EXPERTise 2.0 is a software program that incorporates five tasks that correspond to the RAPID approach to the assessment of cue utilization. The scenarios that comprise the tasks can be tailored to different contexts using visual, auditory, and/or written material. The scenarios comprising the Pool Lifeguarding edition of EXPERTise 2.0 were developed with the assistance of two subject-matter experts, each with more than 10 years experience as a pool lifeguard.

The Feature Recognition Task (FRT) is designed to assess the capacity to accurately recognize patterns of features that are presented for short periods. In the Pool Lifeguarding edition of EXPERTise 2.0, the FRT comprised 16 scenarios, during which participants watched video clips of actual drowning events. Videos were taken from the same angle, and swimmers were labelled using letters A through E. The videos concluded immediately prior to the drowning event, and participants were asked to indicate which of the letters corresponded to the swimmer who would have difficulty within the subsequent 10 seconds. Higher cue utilization is typically associated with a greater frequency of correct responses (Wiggins & O'Hare, 2003).

The Feature Association Task (FAT) is intended to evaluate the strength of association between domain-related features and associated events. Participants attend to a red cross situated in the center of the screen that is subsequently replaced by two stimuli presented simultaneously. Following exposure, participants are asked to rate, using a seven point scale, the extent to which the two stimuli are related. They are advised that they can determine the nature of the relationship. In the Pool Lifeguarding edition of EXPERTise 2.0, the stimuli associated with the FAT comprised text descriptions such as 'pool' and 'lifeguard' that were presented simultaneously for 500 msecs. Greater variance as a proportion of response latency is typically associated with greater cue utilization (Morrison, Wiggins, Bond, & Tyler, 2013).

The Feature Prioritisation Task (FPT) involves the presentation of an initial problem statement that orientates participants to the context. Their task is to acquire information sufficient to formulate an initial response to the problem within 120 seconds. Information is acquired from a list of features presented in random sequence, only one of which may be accessed at any time. In the Pool Lifeguarding edition of EXPERTise 2.0, the problem concerned unexpected advice concerning a child's party that was to be held at the venue and a consideration of the necessary risks and safeguards. A list of 13 features were listed, including the number of parents and children who would be in attendance. Performance on the FPT is assessed by calculating the ratio of pairs of features accessed in the sequence that they were presented to participants as a proportion of the total number of pairs of features accessed. A lower ratio is generally associated with higher cue utilization (Wiggins & O'Hare, 1995).

In the Feature Identification Task (FIT), participants are presented with visual, auditory, or audiovisual stimuli relevant to the domain. They are asked to identify, as quickly as possible, any areas of concern and select the area using the computer mouse. For the Pool Lifeguarding edition of EXPERTise 2.0, the stimuli comprised a series of 20 static visual scenes depicting swimming pool patrons undertaking various activities, from swimming to jumping and running. For the FIT, response latency is recorded, with lower response latency generally associated with higher cue utilization (Loveday, Wiggins, Harris, Smith, & O'Hare, 2013).

The Feature Discrimination Task (FDT) involves the presentation of a problem that is described in detail, incorporating written, visual, and/or auditory information. Participants are asked to consider the problem and indicate, from a list of options, their initial action in resolving the problem. Having indicated their initial action, participants are asked to rate, using a 10 point Likert Scale ranging from 'not important at all' to 'extremely important,' the contribution to their initial action of a range of features that were described in the problem statement. In the Pool Lifeguarding edition of EXPERTise 2.0, the problem described a decision regarding teenagers engaging in unsafe aquatic behaviors at the shallow end of an outdoor swimming pool, while 12 features were listed to which participants responded. Performance on the FDT is determined by calculating the mean variance across the features, with a greater variance generally associated with higher cue utilization (Pauley, O'Hare, & Wiggins, 2009.

2.3. Virtual scenarios

Three virtual reality scenarios were tested, two of which included a drowning victim, while the remaining scenario presented a foil scenario during which no drowning occurred. The scenarios were programmed in Unity and depicted an eight lane, outdoor 50 metre Olympic pool during daylight hours. Participants interacted with the scenarios using an HTC Vive virtual reality headset that enabled an 110° field of view together with a hand controller.

A range of patrons were depicted undertaking different activities, including six children playing using flotation devices at the shallow end of the pool, and five older patrons engaged in lap swimming (see Fig. 1). The older patrons were swimming slowly, with two swimming using a freestyle stroke and three using breaststroke. They were distributed across two lanes and swam in both directions.

In the first of the drowning scenarios, two parents were located on the edge of the pool, adjacent to the children who were all using buoyancy devices. In the second drowning scenario, pre-teenage children were doing handstands under the water without parent supervision but near the simulated pool lifeguard. The pool was surrounded on two sides by a fence, beyond which were grass-covered hills with trees located on the hills. The remaining two sides of the pool comprised walls, with a series of large windows and a doorway that constituted the exit from the pool.

The weather was fine with no clouds nor shadows, although the sun was positioned such that sunlight reflected off the pool water when observing the scene from the east. As is typically the case in pool lifeguarding, a simulated pool lifeguard was always positioned in a location on the opposite side of the pool. While this was intended to ensure a degree of visual fidelity, there was no reference to zones of responsibility for lifeguards. The audio recording presented a typical pool scene with noise from the children and white noise associated with adult conversation.

Participants were positioned initially in the middle of the western side of the pool, but could reposition themselves within two meters of the simulation boundaries. Importantly, participants were able to walk along the edge of the pool but were only able to remain on the western side of the swimming pool.

To minimize expectations as to the nature and the time-period during which the drownings occurred, the target scenarios were 13 minutes and 23 minutes in duration, with the drownings occurring at 10 minutes and 14 seconds, and 19 minutes and 19 seconds, respectively. Both drownings involved older swimmers who were engaged in swimming laps and who descended below the surface of the water, with the body coming to rest at the bottom of the pool. In each case, the drowning was characterized as passive since the absence of conspicuous features such as vocalizations and flailing presents the most challenging situation for drowning detection in practice.

The use of passive drowning scenarios also presented a more robust appraisal of the role of cue utilization in drowning detection. The presentation of the 13 and 23 minute target scenarios was counterbalanced to avoid a practice effect or the impact of fatigue, with a 10 minute control scenario separating the two target scenarios. A three-minute break interval separated the presentation of scenarios with response latency and accuracy in detecting the drowning events recorded for the two target scenarios.

The HTC Vive headset also incorporated internal Tobii eye tracking glasses that were retrofitted and enabled the calculation of fixation and dwell time on the victim prior to and following the drowning event. The Tobii glasses employ a 120 Hz binocular sampling rate to record behavior. Dwell time was recorded as the total time spent fixating on the target swimmer prior to the drowning event.

2.4. Procedure

The Macquarie University Research Ethics Committee provided ethical approval for the study (52021355825005;

Fig. 1. A swimmer in the foreground with another lifeguard and children playing in the background, illustrating the fidelity and characteristics of the virtual scenarios that were employed during the study.

520221129236609). On arrival at the testing laboratory, participants were advised that they would be undertaking a 50 minute, virtual simulated shift as a pool lifeguard. Following the provision of informed consent, the participants completed a demographic questionnaire and entered their age, sex, and experience as a pool lifeguard before completing the Pool Lifeguard edition of EXPERTise 2.0.

On completion of EXPERTise 2.0, participants were advised that their role was to identify any unsafe or inappropriate behavior amongst patrons, consistent with the typical role of a pool lifeguard. The researcher acted as the shift supervisor and participants were asked to verbalize any concerning behaviors that they identified throughout their shift. They were also advised that three minute breaks would be provided periodically between scenarios.

Once the virtual headset had been fitted comfortably, the eye tracker was calibrated, and participants were instructed on the use of the controller to restricting their movements only within the boundaries of the simulated environment. The drowning scenarios were concluded when the participant identified the drowning victim or after three minutes had elapsed following the submersion of the victim. The three minute period was selected as it is considered the maximum amount of time beyond which submersion is likely to result in irreversible physiological damage (Ijeh & Naufal, 2021).

3. Results

3.1. Descriptive results

For each of the target scenarios, the successful detection of the drowning event was limited to a three-minute window following the onset of the drowning event. For those participants who successfully detected the drowning victim, the response latency was recorded from the onset of the drowning event. Total dwell time on the drowning victim was recorded from start of the scenario until the onset of the drowning event. Overall, 49 (56.3%) participants detected the drowning victim in the 13 minute scenario, while 62 (71.3%) participants detected the drowning victim in the 23 minute scenario. Amongst those participants who detected the drowning victim, the mean response latency was 32.64 seconds (*SD* = 35.08) in the 13 minute scenario and 19.66 (*SD* = 31.95) seconds in the 23 minute scenario. The mean time to the first fixation on the victim was 15.96 seconds (*SD* = 24.36) in the 13 minute scenario, and 14.44 seconds (*SD* = 26.4) in the 23 minute scenario. Finally, the total dwell time for participants who detected the drowning victim was 12.13 seconds (*SD* = 6.02) for the 13 minute scenario and 18.40 seconds (*SD* = 10.68) for the 23 minute scenario.

3.2. Expertise 2.0

Performance for each of the EXPERTise 2.0 tasks was aggregated, yielding a mean response latency of 11,512.59 msecs (*SD* = 4,879.36) for the Feature Identification Task, a mean accuracy of 5.54 (*SD* = 2.01) for the Feature Recognition Task, a mean 0.0003 (*SD* = 0.0004) variance as a proportion of response latency for the Feature Association Task, a mean 7.63 (*SD* = 3.11) variance for the Feature Discrimination Task, and a mean 0.77 ratio of pairs (*SD* = 0.21) of information screens accessed in the sequence in which they were listed, as a proportion of the total pairs of information screens accessed, for the Feature Prioritisation Task.

Consistent with previous approaches to categorizations of cue utilization based on performance across the EXPERTise 2.0 tasks, data were standardized and subject to a cluster analysis yielding two groups. Since the EXPERTise 2.0 tasks constitute distinct approaches to the assessment of cue utilization, and the characteristics of cue utilization emerge at different rates due to individual differences in capability and the opportunity for exposure, cluster analysis represents an opportunity to establish a broad overview of the capacity for cue utilization, rather than target a specific capability. Inevitably, this reduces within-subject variability, although it maximizes differences between groups.

Inspection of the centroids indicated that, across the tasks, the two groups reflected a consistent pattern of relatively higher or lower performance, with 23 participants allocated to the higher performance group while the remaining 61 were allocated to the lower performance group (see Table 1). Note that errors in data collection were evident for three participants, the EXPERTise 2.0 data for whom were excluded. A chi-square analysis confirmed that no relationship was evident between categorization on the basis of cue utilization and the sequence in which the 13 minute and 23 minute scenarios were completed, x^2 (1, 82) = 2.08, p =.15.

A chi-square test was used to determine the relationship between the categorization of participants based on their perfor-

Table 1
Centroids based on standardized scores for each of the five tasks that comprise EXPERTIse 2.0, displayed for participants categorized with higher or lower cue utilization.

	Higher Cue Utilization	Lower Cue Utilization
Feature Identification Task	−0.05	−0.03
Feature Recognition Task	0.59	−0.19
Feature Association Task	1.07	−0.38
Feature Discrimination Task	0.64	−0.23
Feature Prioritization Task	−0.79	0.30

Lifeguard Cue Utilization and Employment as a Lifeguard.

mance on EXPERTise 2.0 and their current employment as a lifeguard. Consistent with expectations, the results revealed a statistically significant relationship between categories of cue utilization and previous employment as a lifeguard, x^2 (1, 84) = 5.76, p =.016, with 40.5% of employed lifeguards and 17% of non-lifeguards classified with higher cue utilization. A small to medium effects size was evident, Cramer's V = 0.26.

3.3. Drowning detection

Accuracy during the drowning scenarios was established by summing the number of drowning events that were identified accurately. Therefore, participants could be awarded a score from zero to two. Given the limited range of possible outcomes, a Mann Whitney U was used to compare the accuracy of participants based on their cue utilization. The results revealed a statistically significant effect, U = 354.5, p =.006, with the mean rank for participants with higher cue utilization (Mean Rank = 51.34) exceeding the mean rank for participants with lower cue utilization (Mean Rank = 36.41). This indicates that across the scenarios, participants with higher cue utilization achieved greater accuracy than participants with lower cue utilization.

3.4. Response latency

Given that the response latency data for the 13 minute and 23 minute scenarios failed to approximate normality, the data were subjected to a square-root transformation that resolved the issues. Amongst those participants who detected the drowning victims, separate one-way ANOVAs, comprising the two levels of cue utilization (higher, lower) as a between-groups, independent variable, were used to determine whether there were differences in response latency (transformed) from the onset of the drowning events. With Levene's Statistic non-significant (0.76), no statistically significant differences were evident for the 13 minute, F (1, 45) = 0.69, p =.41, η^2 = 0.02 scenario. Similarly, with Levene's Statistic non-significant (0.83), no statistically significant differences were evident for the 23 minute scenario, F (1, 58) = 0.00, p =.98, η^2 = 0.00.

3.5. First fixation

Initial inspection of the data for the time between the onset of the drowning event and participants' first fixation on the drowning victim revealed that they were non-normal. Therefore, they were subjected to a square-root transformation that resolved the issues for both the 13 minute and the 23 minute scenarios. However, with Levene's Statistics non-significant for both the 13 (0.95) and the 23 minute (0.37) scenarios, separate one-way ANOVAs failed to reveal statistically significant differences between levels of cue utilization for either the 13 minute, F (1, 40) = 0.24, p =.63, η^2 = 0.006 scenario nor the 23 minute scenarios, F (1, 55) = 0.00, p =.98, η^2 = 0.00.

3.6. Dwell time

Since Levene's Test of the dwell time data for the 13 minute scenario was statistically significant, and a transformation failed to correct the distribution, the relationship between cue utilization and dwell time for participants who correctly identified the drowning victim was tested using a Mann-Whitney Test. The results revealed a statistically significant effect, U = 101, p =.03, where participants with higher cue utilization recorded a higher mean rank (Mean Rank = 28.1) than participants with lower cue utilization (Mean Rank = 18.88). No relationship was evident between dwell time and the accuracy with which drowning victims were identified during the 13 minute scenario, U = 294, p = 0.15.

A one-way ANOVA comprising the two levels of cue utilization (higher, lower) as a between-groups, independent variable, was used to determine whether there were differences in total dwell time for successful drowning detection in the 23 minute scenario. No statistically significant relationship was evident between cue utilization and total dwell time, F(1, 55) = 0.60, p =.441, η^2 = 0.01. However, a statistically significant difference was evident in the 23 minute scenario between those participants who were successful and those who were unsuccessful in detecting the drowning victim, F (1, 74) = 4.71, p =.03, $\eta 2$ = 0.06. A subsequent inspection of the means indicated that those participants who identified the drowning victim recorded a greater dwell time on the victim prior to the drowning event (M = 18.91, SE = 1.5) than participants who failed to identify the victim (M = 11.46, SE = 3.8).

4. Discussion

The aim of this study was to determine the relationship between cue utilization and performance as a lifeguard in identifying victims of drowning in 13 and 23 minute simulated scenarios. Participants with and without lifeguard experience were recruited to ensure a breadth of experience. However, it was hypothesised that a relationship would be evident between levels of cue utilization and previous experience as a lifeguard. The results confirmed this relationship with lifeguarding experience associated with 65% of participants who were classified with higher cue utilization.

Consistent with the hypothesis, participants classified with higher cue utilization were more accurate than participants with lower cue utilization in detecting the drowning victims within three minutes of the drowning events having occurred during the 13 minute and 23 minute scenarios. While this is likely due to lifeguarding experience, it also suggests that, consistent with previous research, the acquisition of cues may represent the cognitive mechanism that explains the advantages afforded by experience in detecting drowning victims (Laxton & Crundall, 2018).

No differences were evident in the response latency nor the period for the first fixations on the drowning victim after the drowning event had occurred. However, it is important to note that the analyses were restricted to those participants who accurately identified the drowning victims. Since there were differences in accuracy, it suggests that the response latency and period of first fixation for those participants who accurately identified the drowning victims were broadly equivalent.

In assessing the dwell time on the drowning victim prior to the drowning event, a significant relationship was evident for the 13 minute scenario but not the 23 minute scenario amongst participants who identified the drowning victim successfully. For the 13 minute scenario, participants with higher cue utilization tended to dwell for a greater length of time on the drowning victim than participants with lower cue utilization. No difference in dwell time was evident in the 13 minute scenario between participants who identified or failed to identify the drowning victim. Consistent with the hypothesis, these results suggest that higher cue utilization is associated with a greater capacity to identify potential sources of risk, which then enables the timely detection of drowning victims.

The lack of association evident in the 23 minute scenario between cue utilization and dwell time suggests that there may have been more behaviors associated with the target that were more overt and evidently of some concern, irrespective of the level of cue utilization. This may explain the relationship between greater dwell time and the accuracy with which the drowning victim was identified. Together with the results for the 13 minute scenario, it suggests an inherent capability in identifying behaviors of concern in the context of pool lifeguarding with levels of cue utilization only emerging as a differentiator where behaviors of concern are less overt and more nuanced, reflecting greater precision (Laxton, Mackenzie, & Crundall, 2022).

From a theoretical perspective, the precision that is afforded by greater cue utilization is likely to be associated with a level of domain-related exposure and may explain the capacity for more accurate and rapid detection by constraining attentional resources to a limited number of features that are associated with greater risk. The drowning victim in the 13 minute scenario was an older female patron who was swimming laps at a slow pace. Despite the apparent lack of difficulty, this may have constituted a task-relevant feature for participants with higher cue utilization that drew attention during the preceding period of watch so that when the drowning event occurred, it was detected within the three minute window (Vansteenkiste, Lenoir, & Bourgois, 2021).

The association between cue utilization and constraints on visual processing is consistent with evidence in driving where drivers with higher cue utilization recorded small dispersions of fixations, suggesting that they were targeting specific features (Sturman & Wiggins, 2021). Importantly, these differences in visual processing were also associated with reductions in cerebral oxygenation, consistent with lower demands on cognitive load.

In addition to drawing attention to salient features and reducing the demands on cognitive load, higher cue utilization has been associated with improvements in sustained attention since it reduces the rate at which cognitive resources are consumed during a vigil (Sturman et al., 2020). In effect, this prolongs the period during which cognitive resources are available, extending the period of active engagement over the visual scene. This increases the likelihood that changes in the visual scene will be identified quickly and accurately.

At an applied level, the results suggest that it may be possible to assess cue utilization as a marker of expertise in the context of lifeguarding and thereby identify the need for training and provide feedback during and following training. As an assessment tool, EXPERTise 2.0 represents an opportunity to evaluate performance quickly and cost-effectively across a wide range of scenarios, much like the edition that has been created for water safety-related cue utilization (Wiggins et al., 2019). It also potentially obviates the need to devise and undertake manikin-based evaluations that occupy part of a pool, avoids priming trainees to the prospect of an evaluation, reduces the risk of an association with features that are not necessarily engaged in practice, and enables performance to be captured that applies to a range of scenarios. Importantly, it enables comparative analyses potentially informing decisions concerning the allocation of training resources at both a cohort and at an individual level.

As a construct, cue utilization could also be employed as the basis for training initiatives. For example, capitalizing on advances in simulation and virtual environments, it is possible to construct realistic environments that incorporate critical cues that have been identified as precursors to drowning (Lim, Wiggins, Porte, Bayl-Smith, Curby, Olsen, & Taylor, 2023). Trainees can be exposed to these cues under a range of conditions, including perceptual constraints, such visual occlusion and reflections, and attentional demands, including distractions and the requirement for sustained attention (Laxton et al., 2022). In developing both the repertoire of critical cues and the nature of their presentation, lifeguards can be better prepared to anticipate and thereby respond rapidly to incidences of drowning in public pools.

4.1. Limitations and future research

Although the results suggest that higher cue utilization is associated with more accurate detections of drowning events, the evaluation in the present study was constrained to two simulated scenarios, both of which involve passive drowning in a public pool. While VR simulations were used to enable the evaluation of a range of scenarios, and passive drowning was employed since it is the more difficult form of drowning to detect, the extent to which the features correspond with features in the operational context is unclear. Although there is undoubtedly a degree of realism evident in the scenarios, constructing and testing additional scenarios and demonstrating differences in sensitivity would provide a greater level of confidence concerning the fidelity of both the VR environment and the drowning-related scenarios.

Extending the length of the scenarios would also contribute to their fidelity, since lifeguarding shifts can extend to four hours. In the present study, the target scenarios were limited to 13 and 23 minutes and may have constrained any differences in performance that might have been attributed to sustained attention over an extended period. Further, although the scenarios incorporated visual and auditory distractions, including children playing, there were no intentional interruptions. Lifeguards experience interruptions on a regular basis in practice and sustaining attention while managing interruptions is an important capability. Therefore, in testing further the relationship between cue utilization and lifeguarding performance, scenarios should progress over an extended period before the drowning event occurs and should include interruptions and other events for which lifeguards are responsible, such as unsafe or inappropriate behavior.

While the limited period within which the detection of the drowning event needed to occur during scenarios was consistent with the potential for the loss of life, it also limited the opportunity to detect the drowning patron and thereby restricted the response latency and the period for first fixations. This may explain the lack of variability between higher and lower cue utilization despite differences in accuracy. To establish the nature of the relationship between cue utilization and response latency and first fixations on drowning victims, it may be necessary to extend the minimum period for detection beyond that necessary for the survival of swimmers and consider different levels and types of experience amongst lifeguards.

5. Conclusion

The aim of this study was to examine the relationship between cue utilization and the detection of drowning victims in virtual simulated scenarios in a public swimming pool. Participants with and without experience as a lifeguard completed three scenarios, two of which were target scenarios where a patron drowned after either 13 minutes or 23 minutes. As expected, a relationship was evident between experience as a lifeguard and levels of cue utilization where lifeguards were more likely to record performance consistent with higher cue utilization.

Participants with higher cue utilization were also more accurate in detecting the drowning victim within a three-minute window of opportunity and, in the case of the 13 minute scenario, recorded a greater dwell time on the drowning victim prior to the drowning event. This suggests that cue utilization, as measured by EXPERTise 2.0, differentiates performance in simulated drowning scenarios in public swimming pools and that this might be explained by a greater propensity to target critical features that are associated with potential risks.

From an applied perspective, the outcomes offer a potential opportunity to assess lifeguarding performance quickly, cost-effectively, and safely across a range of different scenarios. With additional research, it should enable the application of training and development initiatives at both a cohort and at an individual level, thereby ensuring that amongst novices, the appropriate skills are acquired, and amongst lifeguards with greater experience, that these are maintained.

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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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Linking occupational accidents and construction firm survival

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A B S T R A C T

Introduction: This paper examines the relationships between the reported accidents of workers in construction firms and the probability of those firms' survival. *Method:* Between 2004 and 2010, a sample of 344 Spanish construction firms from Majorca were selected. The study built panel data with the reported official accidents from the Labor Authority records and the firm survival or mortality from the Bureau van Dijḱs Iberian Balance Sheet Analysis System database. The hypothesis is that a higher number of accidents directly affects the probability of the company surviving in the sector. By using a probit regression model with panel data, the relationship between these two variables were explored to test the hypothesis. *Results:* The study found evidence that an increment in accidents decreases the probability of the company continuing to operate, or worse, going bankrupt. The results can be useful to highlight the importance of defining policies to control those accidents effectively, since this may be a key factor in the sustainability, competitiveness, and growth of the construction sector for the economy of a region.

1. Introduction and literature review

The construction sector is widely known for its poor performance in health and safety (H&S) matters. Data have shown that construction is one of the sectors with the highest accident rate (Ahn et al., 2022; Jin et al., 2019). In 2018, more than 2.78 million people died due to an accident or disease at work (ILO, 2019).

On the one hand, there is a broad consensus on the need for investing in H&S in organizations. The high cost of the failure in prevention investment was expressed in the XXI World Congress of Health and Safety at Work, when the Director of the International Labour Organization stated that "The economic impact of failing to invest in worker safety and health is nearly equal to the combined gross domestic product of the 130 poorest countries in the world" (Ryder, 2017, 3:55). The evidence has shown that a higher investment in prevention reduces occupational accidents by diminishing the level of risk (Forteza, Carretero-Gómez, & Sesé, 2017; Sousa et al., 2021). However, it is not known to what extent the relationship between prevention investment and accidents can affect the company's performance or its eventual survival. Many studies have pointed out that the construction sector is characterized by a high number of small companies that operate with few resources and poor safety management systems (Segarra et al., 2017; Wang et al., 2019). The evidence shows that these kinds of companies tend to ignore any safety costs as well as the final impact that these have on their economic results, and ultimately on their survival (Cagno et al., 2011). Therefore, it seems relevant to study to what extent the survival of these companies can be explained by their workers' accidents, due to their H&S management. A recent study claims that a better financial performance can be obtained by increasing the occupational safety measures (Sousa et al., 2021). Going a step further, this study aimed to examine whether fewer accidents decrease the probability of a firm failure. This evidence can be a strong argument to persuade practitioners to view effective H&S measures not just as a cost, but as an investment with important returns, such as the survival of a firm.

It seems that the impact of H&S on the companies' costs and incomes has been analyzed separately. On the one hand, there is literature examining the economic impact of H&S in the workplace, mostly aimed at estimating its total cost, which is composed of prevention costs and accident costs (Chen et al., 2021; Feng et al., 2015; Ibarrondo-Dávila et al., 2015). However, assessing the safety costs is a difficult task, as the current assessment tools are not able to include all their components (Ahn et al., 2022). One of the drawbacks regarding the estimate of the total costs of occupational accidents is the lack of visibility of the H&S costs, since more than 90% are not considered in the accounting system of the firm (Ibarrondo-Dávila et al., 2015; Sousa et al., 2015).

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Therefore, those are hidden costs that impact the business without previous notice, and they are only perceived as relevant when something unexpected happens. Even though there is general agreement about the importance of investing in H&S, in terms of social welfare, the evaluation of safety costs at firm level is still an open research question (Cagno et al., 2013; Toutounchian et al., 2018).

Furthermore, some studies have found evidence for the link between lower accidents and higher earnings in firms and a higher GDP in countries (Li et al., 2021). According to ILO (2019), work accidents represent 4% of the world's GDP and there is a positive correlation between several economic indicators and the reduction of workplace accidents.

Some authors have also claimed theoretically that H&S is a relevant factor that affects the managers' success as well as the economic results of the firms and, consequently, their competitive advantage (Rechenthin, 2004; Teo & Ling, 2006). Understanding how the economic evaluation of H&S performance in a firm is related to the company results is a relatively recent issue in the literature, although it is a research priority (Cagno et al., 2013). Some other authors have suggested that H&S at work is mainly seen more as a blind accomplishment of rules and regulations than a managerial issue with an economic return for the company (Fernández-Muñiz et al., 2016; Njå & Fjelltun, 2010). Due to the apparent practitioner disregard of the benefits of H&S investment, it seems relevant to find out how H&S costs affect the economic performance of a company by connecting the "safety" argument with the "productivity" goal (Biddle et al., 2005; Sousa et al., 2021). This study offers a step in this direction.

In a recent literature review on the relationship between safety investment and financial performance, Sousa et al. (2021) concluded that there is a positive relationship between promoting occupational safety measures and the firms' financial benefits. This benefit is also stated in the International Social Security Association report, which highlights a positive economic return ratio of 2.2 of the company's occupational safety and health investment (ISSA, 2011, p. 7).

Summing up, as Rechenthin (2004) concluded, effective safety management can help construction companies to achieve a sustainable competitive advantage through good safety performance. Also, there is general agreement in the literature that bad performance in H&S issues, such as a high number of accidents per worker, can generate such significant costs that all benefits of the firm may vanish, thus threatening its financial stability and even its survival in the mid or long-term (Kim & Park, 2021; Sousa et al., 2021).

Based on the previous discussions and in line with the theoretical insights from Rechenthin (2004) and Teo and Ling (2006), this study proposes to empirically test whether a high number of accidents per worker is associated with a higher mortality in construction companies. Thus, the hypothesis to be tested is the following:

H1. A higher number of accidents per worker of a construction company is associated with a higher probability of failure of that company.

Following, the study describes the most relevant aspects of this empirical strategy and methodology. Then, the authors report the results of the estimation strategies and discuss them in detail. Finally, the paper presents the conclusions and final remarks.

2. Methodology

2.1. Model specification

The hypothesis is aimed at modeling the probability of a company's failure. Table 1 summarizes the names, codes, and definitions of all the dependent and independent variables considered in this paper. Probit and logistic regressions are adequate statistical techniques for modeling the impact of a set of independent variables on a dependent variable that takes the values of 0 and 1 (Long, 1997). Since probit and logit yield similar results, the election of the method to use depends on the researcher's preference, and one of the interesting aspects of these techniques is that predicted probabilities can be computed based on the estimation results for given values of the independent variables (UCLA: Statistical Consulting Group, 2017). Model specifications for testing the hypothesis are as follows:

Model specification:

$$STATE_{i,t} = \alpha + \beta_1 \cdot ACCIDENTSW_{i,t-1} + \beta_2 \cdot .\ ROA_{i,t} + \beta_3 \cdot SALESW_{i,t} + \beta_4 \cdot ASSETURN_{\ i,t} + {}_{i,t} \text{ (model 1).}$$

$$STATE02_{i,t} = \alpha + \beta_1 \cdot ACCIDENTSW_{i,t-1} + \beta_2 \cdot ROA_{i,t} + \beta_3 \cdot SALESW_{i,t} + \beta_4 \cdot ASSETURN_{i,t} + {}_{i,t} \text{ (model 2).}$$

The dependent variable in model 1, *STATE*, is a discrete variable with three levels, adding to the values of *STATE_0_2* another intermediate situation in which companies may fall between going bankrupt and running with normal activity. This intermediate situation is called the state of "concurso de acreedores" according to Spanish regulations. It is the legal situation of a business with serious problems of continuity in which a new CEO is appointed by the Courts and has to either relaunch the firm or dissolve and wind it up. Depending on how critical the situation is for the company, it could continue with its committed activities under this state. In this situation, the firm cannot be classified clearly as a failure or

Table 1
Codes and definitions of variables regarding occupational accidents, construction firm survival and economic indicators.

Variable	Code	Values/Description
Event of firm survival	*STATE*	0 Firm went bankrupt 1 Firm went in an insolvency procedure[a] 2 Firm is up and running
	STATE_0_2	0 Firm went bankrupt 1 Firm is up and running
Firm accidents per worker	*ACCIDENTS_W*	Total number of accidents divided by total number of workers
Return on assets	*ROA*	Measure of firm profitability calculated as the net income of the firm divided by the average total assets of the firm
Sales volume per worker	*SALES_W*	Indicator of firm activity which is computed as the revenue obtained by the selling of products or services divided by the total number of workers of the firm
Asset turnover	*ASSETURN*	Proxy of organizational efficiency which is equal to the firm sales volume divided by its total assets

[a] "Insolvency procedure" is the translation of the firm state "*concurso de acreedores*".

a survival case. Therefore, this study proposes model 1 to test for any different impact that accidents would have on each of these three operation states.

The dependent variable in model 2 is dichotomous. The variable *STATE_0_2* takes the value of 0 if the company went bankrupt and 1 if it is up and running, both at the end of the period.

2.2. Independent variables

The accidents per worker (*ACCIDENTS_W* in models 1 and 2) is defined as the total number of accidents in a company in one particular year divided by the total number of employees from that firm in that year. Obviously, the authors recognize that the occurrence of either an accident or the company failure can be affected and explained by many other factors beyond the H&S conditions. For this reason, in the two models, some control variables are added that are usually considered in the empirical business literature to account for financial and operational/managerial performance (Fairfield & Yohn, 2001; Tan & Wang, 2010). One of these variables is the return on assets (ROA), which is an index of the firm's financial performance. *ROA* in this study's models is computed as the net income of the firm divided by the average total assets of that firm, and it explains how profitable the set of assets of a company is for generating revenues. Another variable usually considered in empirical studies to measure the volume of activity is the revenue obtained from the selling of products or services. In this study's models, *SALES_W* is included, which is the sales volume divided by the total number of firms' workers. Additionally, the variable asset turnover (firm sales volume divided by its total assets) is frequently used as a proxy of organizational efficiency, therefore this variable (*ASSETURN* in our expressions) is introduced in the same way as in Argilés-Bosch et al. (2014, 2020) and Forteza et al. (2017).

2.3. Sample and data collection

This study sampled 344 construction companies from Majorca (Balearic Islands). This is a random subsample extracted from a total sample composed of the 627 construction companies that registered 957 work site opening notifications (this refers to a compulsory notification by which all contractors have to notify the Labor Authority each time that they are going to start a new project) from the Labor Authority database. Therefore, many of these companies and sites were operative. From the list of companies registered, the authors randomly selected 1 out of 2 to 5 opening notifications, depending on the notification level in each particular year. Once the sample of the 957 sites was built, the authors randomly selected the final sample using a computer algorithm selection (subsample error = 3.55 % at 95% of statistical confidence). This database was crossed with the reported accidents of construction companies database from the Balearic Islands Labor Authority and with the Bureau van Dijk's SABI database, which contains financial and economic data of a number of companies.

2.4. Methodological issues

It is plausible to assume that the observations of a variable for a firm have certain inter-dependence across time (i.e., for a firm the observed value of a variable in period t will be related to the observed value of that variable in period $t+1$). In other words, the variables might be generated under a particular time process. This would be related to the non-stationarity of the variables, and it opens the possibility of co-integration between them. With long panels and linear models, a test for co-integration must be performed to check if the variables have a stable relationship in the long term. Without testing for non-stationarity and co-integration, the estimation results can capture common trends if the variables are co-integrated. This can be an issue when researchers want to discuss some causal relationship between variables.

In order to deal with the possible interdependence of observations of a variable across time for the same firm, the authors propose to estimate the models by calculating the standard errors forming clusters, where those clusters are the observations of each firm; due to the fact that this panel covers a short time span (2004–2010), it is unbalanced and these models are non-linear. For robustness checks, the authors also proposed to perform robust estimations for all models.

Another methodological issue is related to causality. With the current data set, the authors cannot perform quasi-experimental methods to make causal inferences such as, for example, difference in differences or instrumental variable analysis. Consequently, the empirical method is developed upon hypotheses of associations between variables instead of cause-and-effect theories. In this hypothesis, the authors are interested in analyzing the relationship between the accidents per worker and the probability of a firm failure. It is quite plausible that the impact of accidents on the ability of a firm to survive takes a certain time to occur. This delayed impact would be consistent with recent evidence on the relationship between the accident and the firm economic performance found by Argilés-Bosch et al. (2014, 2020). These authors found a significant negative effect of occupational accidents on the firm profitability, with a greater effect of accidents on the firm performance after one year. Based on this finding, the probability that a company survives in period t depends on the accidents reported in period t-1. Despite this specification, this study takes any causality interpretations very cautiously.

Finally, in all this study's estimated models, the authors added control variables for specific time effects using dummies for years as is usual in similar studies.

3. Results and discussion

Table 2 reports the frequency of observations in the sample for each level of the dependent variables, and Table 3 shows the sample descriptive statistics for the variables of these models.

Table 4 reports the Pearson correlation matrix for relevant variables of these models. As can be observed, the discrete dependent variable in model 1 (*STATE*) shows significant correlations with most of the control variables. The variable *STATE_0_2* is not included in the correlation matrix because it is a subsample of the variable *STATE*. However, for the hypothesized effects, the event of survival (*STATE*) does not show a significant correlation

Table 2
Frequencies of dependent variables: Construction firm survival (STATE and STATE 0_2).

Variable: Event of firm survival (*STATE*) (Discrete variable)	**Freq.**[a]	**Percent**	**Cum.**
0 Firm went bankrupt	759	33.85	33.85
1 Firm went in an insolvency procedure[b]	167	7.45	41.30
2 Firm is up and running	1,316	58.70	100.00
Total	2,242	100	
Variable: Event of firm survival (*STATE_0_2*) (Dichotomous variable)			
0 Firm went bankrupt	759	36.58	36.58
1 Firm is up and running	1,316	63.42	100.00
Total	2,075	100	

[a] For a given firm it can take one value per year from 2004 to 2010. It is an unbalanced panel.
[b] "Insolvency procedure" is the translation of the firm state "*concurso de acreedores*".

Table 3
Summary statistics of variables regarding occupational accidents, construction firm survival and economic indicators.

Variable	N	Mean	Std. Dev.	Min	Max
ACCIDENTS_W	2242	0.11	0.20	0	2.67
ROA	1734	−0.01	23.95	−429.19	68.19
SALES_W	1551	183.36	471.93	0.77	8291.01
ASSETURN	1662	4.27	116.23	0.00	4739.75

Note: *ACCIDENTS_W* is the total number of accidents divided by total number of workers; *ROA* is the percent of return on assets; *SALES_W* is the revenue obtained by the selling of products or service divided by the total number of workers of the firm; *ASSETURN* is the firm sales volume divided by its total assets.

Table 4
Pearson correlations of variables regarding occupational accidents, construction firm survival and economic indicators.

	STATE	***ACCIDENTS_W***	***ROA***	***SALES_W***	***ASSETURN***
STATE	1				
ACCIDENTS_W	0.03	1			
ROA	0.11***	0.07***	1		
SALES_W	−0.01	−0.05*	0.06**	1	
ASSETURN	−0.04*	−0.01	0.05*	0.00	1

*Significance level: $p < 0.1$; **Significance level: $p < 0.05$; ***Significance level: $p < 0.01$.
Note: *STATE* is the event of firm survival; *ACCIDENTS_W* is the total number of accidents divided by total number of workers; *ROA* is the percent of return on assets; *SALES_W* is the revenue obtained by the selling of products or service divided by the total number of workers of the firm; *ASSETURN* is the firm sales volume divided by its total assets.

with the accident per worker (*ACCIDENTS_W*). According to the significant correlations, having an accident in a company is positively correlated with the size and volume of the business. Regarding the firm survival event, which is measured by *STATE*, the significant correlations also suggest that bigger and more profitable businesses with less asset turnover are associated with fewer failure events. Even though the correlation between firm survival and the accident per worker is low and not significant, the sign for this relationship is positive, suggesting a pairwise behavior against the hypothesis.

Several appropriate empirical strategies were used for testing the hypothesis with the data set. For model 1, ordered probit regression method was used to fit regression models with discrete dependent variables (*STATE*). Finally, probit regressions (pooled) were used for model 2 as there was a binary dependent variable (*STATE_0_2*). As explained above, in models 1 and 2 the study regressed the corresponding dependent variable of the event of the firm survival on the independent variable "accident per worker" with one period lag, including other control variables. Models 1 and 2 cannot fit as panel data (random effects), as the with-in variance in the dependent variable for most cases in the sample is low. As mentioned above, due to the plausible interdependence that can exist between observations of a variable for a given firm across time, the models were fit specifying that the standard errors allow for intragroup correlation, considering each firm as an independent cluster. All the results in Table 5 follow that cluster estimation procedure, with the exception of the results reported in columns (2a) and (4b) of Table 5, where the Huber-White robust standard errors estimations were used to control for heteroskedasticity. To detect multicollinearity, after the regression analysis, the authors performed the mean variance inflation factor (vif) analysis of variables, obtaining 1.40 for the models, which is lower than the tolerable limit of 10 (Wooldridge, 2009).

In addition, dummies for the years from 2005 through 2010 were included, considering that 2004 is the default year. STATA 14.2. was used to fit the models.

The hypothesis of this paper is to analyze whether H&S results affect the survival of the construction firm. The study proposes to test this hypothesis by using two alternative specifications, model 1 and 2. In model 1, the dependent variable *STATE* can take three values (0 = when the firm went bankrupt; 1 = when it followed an insolvency procedure; and 2 = when the firm stays up and running). Due to the characteristics of this variable, the appropriate method that fits this model is an ordered probit regression. Model 2 is fit with the same data sample but excluding the 25 construction firms that went through an insolvency procedure during the analyzed period, that is, the dependent variable (*STATE_0_2*) takes two values (0 when the firm went bankrupt; and 1 when the firm is alive). The dependent variable of interest is *ACCIDENTS_W LAGGED*, which is the firm accident per worker of the previous year.

Table 5 shows the results of estimations after fitting model 1 for *STATE* and model 2 for *STATE_0_2*. Columns (1) and (3) display the baseline models, and columns (2) and (4) show the full models estimated using clusters. Finally, columns (2a) and (4a) include the full model with standard Huber-Wright errors robust estimations. As it can be seen, Table 5 shows similar results for both models supporting the hypothesis and confirming the predicted effect that more accidents per worker harm the probability of a firm to survive one year later.

The overall evaluation of the models is quite good according to the confirmation of the goodness of fit of all the specifications. Table 5 reports the Likelihood-ratio tests, which are all significant at the confidence level of 99%. Both baseline specifications showed in column (1) and column (3) of Table 5 yield significant parameter estimates for *ROA* and significant coefficients for some years of the panel. Therefore, these results support the expected positive impact of profitability (measured by *ROA*) on survival. Although the fitted models give small estimated parameters of the *ROA* variable (0.01) (see Table 5 columns (2) and (4) respectively), the effects are strongly significant with *p-values* < 0.01. The variables sales per worker (*SALES_W*) and asset turnover (*ASSETURN*) have a negative estimated effect on the ability of a firm to survive, although their parameters are not significant. In the case of sales per worker (*SALES_W*) that are usually used as a proxy of firm activity, the coefficient in model 1 is −0.35e-04 (see column (1) in Table 5) with a *p-value* of 0.761. For model 2 the *SALES_W* coefficient has an estimated value of −0.41e-04 with a *p-value* of 0.719 (see column (3) in Table 5). Concerning *ASSETURN*, usually considered as a proxy of firm efficiency, the coefficient has a non-significant value of −0.04 (model 1, column (1) in Table 5), and a similar result is obtained in model 2 (column (4) in Table 5). There is not a clear explanation for this last counterintuitive result. One possible explanation is that the negative sign of this coefficient might show certain consequences of some years of the economic

Table 5
Model 1 and model 2 – Hypothesis 1: Effect of the accidents per worker of a firm (*ACCIDENTS_W*) on the event of construction firm survival (*STATE* and *STATE_0_2*).

Variables	**Model 1** **Dependent variable = *STATE*** (pooled ordered probit regression)			**Model 2** **Dependent variable = *STATE_0_2*** (pooled probit regression)		
	(1)	**(2)**[a]	**(2a)**[b]	**(3)**	**(4)**[a]	**(4a)**[b]
ACCIDENTS_W LAGGED		**−0.25***	−0.25**		**−0.26**	**−0.26****
ROA	0.01***	0.01***	0.01***	0.01***	0.01***	0.01***
SALES_W	−0.35e-04	−0.41e-04	−0.41e-04	−0.41e-04	−0.48e-04	−0.48e-04
ASSETURN	−0.04	−0.03	−0.03	−0.04	−0.02	−0.02
YEAR						
2005	−0.04			−0.04		
2006	0.01	−0.04	−0.04	0.01	−0.06	−0.06
2007	0.13**	0.11*	0.11	0.14*	0.12	0.12
2008	0.34***	0.27***	0.27**	0.38***	0.30***	0.30**
2009	0.50***	0.44***	0.44***	0.56***	0.50***	0.50***
2010	0.67***	0.63***	0.63***	0.71***	0.67***	0.67***
/cut1	−0.56	−0.63	−0.64			
/cut2	−0.33	−0.41	−0.41			
_cons				0.48***	0.55***	0.55***
Goodness of fit	LR $Chi^2(9)$ = 68.55***	LR $Chi^2(9)$ = 70.27***	LR $Chi^2(9)$ = 55.41***	LR $Chi^2(9)$ = 63.00***	LR $Chi^2(9)$ = 65.89***	LR $Chi^2(9)$ = 53.27***
Pseudo R-squared	0.03	0.04	0.03	0.05	0.06	0.06
No. of observ.	1550	1269	1550	1437	1178	1178

*Significance level: $p < 0.1$; **Significance level: $p < 0.05$; ***Significance level: $p < 0.01$.
[a] Model with cluster estimation.
[b] Model with standard Huber Wright robust errors estimations.
Note 1: *STATE* is the event of firm survival (three level variable); *STATE_0_2* is the event of firm survival (binary variable); *ACCIDENTS_W LAGGED* is the total number of accidents divided by total number of workers one year before; *ROA* is the percent of return on assets; *SALES_W* is the revenue obtained by the selling of products or service divided by the total number of workers of the firm; *ASSETURN* is the firm sales volume divided by its total assets; *YEAR* is the dummies for years.

recession suffered during the period analyzed in this paper. This recession was especially harmful for the construction industry, where many firms liquidated their assets. Regarding year dummies, this study found significant effects in the second half of the panel, signaling the existence of such time contextual circumstances. Those effects are more clearly detected from 2008 on, and they increasingly expand in time, which is probably related to the global financial crisis that presumably had an impact on the survival of the firms during that period.

Full model 1 (see columns (2) and (2a) in Table 5) specifies that the effect of the accident per worker lagged one year (*ACCIDENTS_W LAGGED*) and other control variables over the three levels variable of survival (*STATE*). The marginal effect of the accident per worker on the probability of survival for a firm is negative, −0.25, and significant at 90% confidence using cluster estimation (column (2)) or at 95% confidence with robust estimations (column (2a)).

In full model 2 the authors limit the analysis to both alive and bankrupted firms, thus excluding those firms in the intermediate state of insolvency procedure (see columns (4) and (4a) in Table 5). By doing so, the authors regress the binary variable of survival (*STATE_0_2*) on the same set of independent variables used in model 1. As it can be seen, similar results are found in both models. For cluster estimation (column (4)), the estimated marginal effect of the accident per worker on the probability of surviving is negative, −0.26, but not significant (*p-value* = 0.122). However, by fitting the same model with the Huber Wright robust standard errors (column (4a) in Table 5), the coefficient takes the same magnitude, −0.26, but it is significant at an alpha of 0.05 (*p-value* = 0.040).

In short, these results support the hypothesis, and the evidence is stronger for robust estimation methods. It is concluded that, when a construction firm starts to suffer an increase of accidents per worker one year, it can be predicted that this increment will be associated with a higher probability of struggling to be operational the following year. For the company, this would mean falling into an insolvency procedure, or even worse, going bankrupt. Even though this analyses does not allow a claim for causality, it is assumed that the effect of a high number of accidents per worker may have an impact on the probability of surviving the following year. It is reasonable to consider that the transfer of the effects of accidents per worker on the firm's performance (and possibly its survival) will happen over a period of time. This interval can be associated with the time needed to conduct appropriate accident investigations and analyze reports for identifying the possible causes, errors, and responsibilities. As can be seen, the literature shows empirical evidence of a one year lag in the effect of accidents per worker on the firm's economic performance (Argilés-Bosch et al. 2014, 2020). Notwithstanding, this study checked the existence of a relationship between survival and the accidents per worker in the same year, and found similar results to those in Table 5 (these results are not reported in this paper for the sake of length; they are available upon request from the authors).

These results are also in line with many of the previous theoretical and empirical studies analyzing the economic effects of H&S, which have been reviewed above. It was found that the negative impact of a high number of accidents per worker on the probability of a company's survival reinforces Rechenthin's (2004) conclusion that effective safety programs have a relevant role in constructing a sustainable competitive advantage for companies. The evidence in favor of hypothesis 1 also provides empirical insights related to some of the propositions in Chen et al. (2021). For example, these authors proposed that the cost/risk perception ratio should be considered when studying and framing issues of safety economics. Since construction is characterized as a high-risk industry (Rechenthin, 2004, p. 307), one can assume that the managers of construction firms might be less risk-averse compared to other colleagues of less risk industries. Chen et al. (2021) proposed that risk-tolerant managers may underestimate the financial consequences of unlikely accidents and neglect the risk. It is expected that when the evidence that the consequences of underestimated accidents can eventually end with the failure of the company is given to this kind of person, they will see clearer incentives to invest in safety barriers or implement more effective safety measures. As Argilés-Bosch et al. (2014, 2020) found, labor accidents have a negative impact on financial performance, and therefore, their results are also consistent with those in this study. They studied a large variety of industries, not all of them with the same level of industry specific risk, nor with the same prevalent accident rate. Due to the high number of accidents that is prevalent in the construction sector, Argilés-Bosch et al. (2014, 2020) results imply that the negative impact on financial performance (i.e., in ROA) can be greater in this sector than in other safer sectors, and therefore more insolvency situations can be generated in the construction sector. It will be interesting to contrast this with crossed-industry studies to analyze the probability of company survival as a function of the occupational accidents of companies. Under similar arguments, the authors also find these results compatible with those from Forteza et al. (2017). Due to the high accidents per worker in construction companies, more companies will fall in the decreasing part of the quadratic function of ROA when explained by the number of accidents, and it is well known that less profitable companies are eventually more likely to fail.

The authors believe the evidence presented in this research represents a relevant contribution to the literature devoted to highlighting the relevance of effective and efficient H&S management. These results reinforce the message that investing in effective H&S measures reduces accidents per worker and, finally, contributes to the sustainability of construction companies. Therefore, managers can find from this study a solid argument to defend that investing in H&S measures to reduce the number of accidents at work is an attractive decision, if not a vital one.

4. Conclusions and final remarks

This paper analyzed whether the accidents per worker in a construction company is a determining factor in its survival. Although this hypothesis can be generalized to any other economic activity, the construction sector is an interesting setting for testing it, as it is one of the sectors with the highest number of accidents per worker, and consequently with economic and social losses. As was reviewed, there are not many empirical studies that prove how having a safer firm is a good alternative for helping it build a competitive advantage. Obviously, closing up the business because of financial insolvency is a consequence of losing the battle for competitiveness.

The authors believe this research provides sound empirical evidence of the potential strategic value of promoting, implementing, and maintaining effective H&S management that helps reduce accidents in an organization. A relevant sample of construction firms was built. Furthermore, the study rigorously applied appropriate methodologies for studying and testing the hypothesis.

The study did find significant evidence supporting that hypothesis. According to the results, it can be concluded that there is a significant effect of accidents per worker in a construction company on the probability of it failing as a business. When a construction firm that operates normally starts to suffer an increment in its occupational accidents, it can be predicted that its probability of struggling to continue operating (falling into an insolvency procedure, or worse, going bankrupt) will rise as well.

Future research can address some of the following topics to overcome the limitations of this research: (a) studying the process of a changing state from active to bankrupt by looking at individual cases; (b) introducing the organizational design variable as determinant for the probability of having accidents; (c) considering other periods outside the years of economic crisis (2008, 2009, etc.), as they may have a significant effect on the company failure, not because of H&S issues but due to low revenues or excessive debt. The authors hope these limitations will inspire future research that will focus on the connections between H&S performance and the economic results of construction firms.

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Declaration of interest statement

The authors declare that they have not any conflict of interest.

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PPE non-compliance among construction workers: An assessment of contributing factors utilizing fuzzy theory

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ABSTRACT

Introduction: Construction practitioners are at a disproportionately higher risk of fatal and nonfatal injuries compared to practitioners from other industries. The absence of and inappropriate use of personal protective equipment (PPE), hereinafter referred to as PPE non-compliance, are major causes of fatal and nonfatal injuries at construction workplaces. *Method:* Accordingly, a robust 4-step research methodology was employed to investigate and assess factors that contribute to PPE non-compliance. As a result, 16 factors were identified utilizing literature review and ranked utilizing fuzzy set theory and K-means clustering. Top among them: inadequate safety supervision, poor risk perception, lack of climate adaptation, lack of safety training, and lack of management support. *Results:* Managing construction safety in a proactive manner is vital to eliminate or minimize construction hazards and improve overall site safety. Thus, proactive measures to address these 16 factors were identified utilizing a focus group methodology. The validation of the statistical findings with that of the focus groups of industry professionals provides validation of the findings as both practical and actionable. *Practical Applications:* This study significantly contributes to construction safety knowledge and practice which, in turn, aids academic researchers and construction practitioners in their continuous efforts to reduce fatal and nonfatal injuries among construction workers.

1. Introduction

The U.S. construction industry has maintained an average share of fatalities (~20%) that is greater than its average representation within the overall workforce (~4.3%) for the last 10 years. In 2020, the construction industry's share of fatalities was 21.2% (i.e., 1,008 fatalities), whereas its representation within the overall workforce was 4.1%. Fig. 1 shows the fatal injury data by industry and the construction occupation employment estimates from the U.S. Bureau of Labor Statistics (BLS, 2021).

To better understand the numbers presented in Fig. 1 and the disparity in fatalities between construction workers and non-construction workers, an odds ratio was calculated utilizing the numbers of fatalities among construction workers and non-construction workers, along with their representation in the U.S. workforce. Equation (1) was used to calculate the odds ratio by the research team for the years between 2010 and 2020.

$$\textit{Odds Ratio} = \frac{p/(1-p)}{q/(1-q)} \tag{1}$$

Where:

p: Percentage of fatalities among construction workers in a specific year (fatality cases/construction population).
q: Percentage of fatalities among all workers, not including construction workers in a particular year (fatality cases/all workforces not including construction).

The overall resulting odds ratio for the 2010 to 2020 period was 5.57 (95%; confidence interval (CI): 5.45–5.65). This result indicates that construction workers, on average, are 5.57 times more likely to be killed than non-construction workers in U.S. workplaces. The 95% CI of 5.45 to 5.65 means that one can be 95% confident that the true odds ratio lies somewhere between 5.45 and

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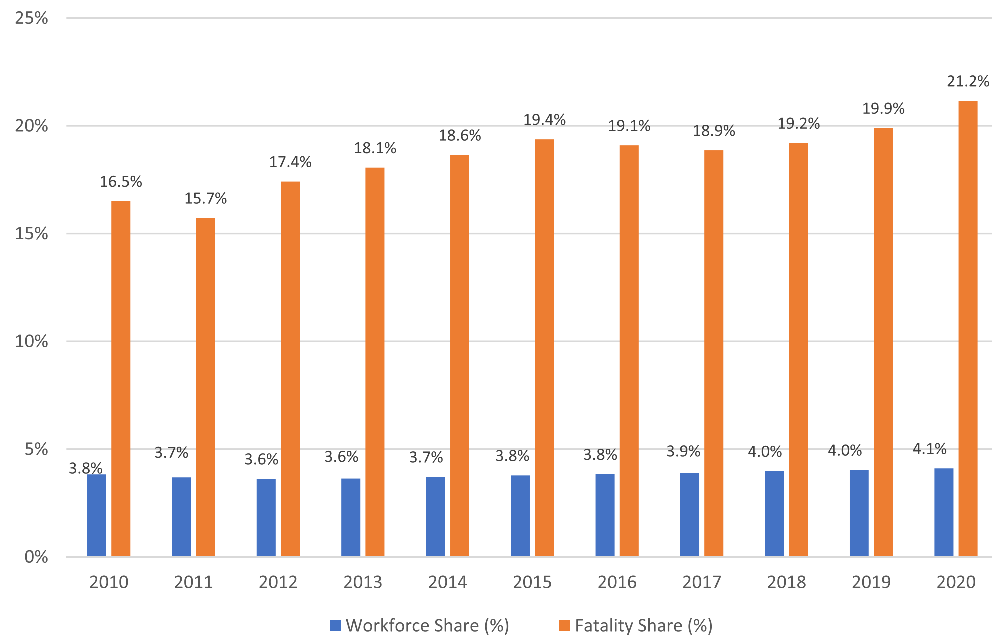

Fig. 1. Construction Workforce and Fatality Shares.

5.65. A 95% confidence interval that does not eclipse 1.00 would commonly be interpreted as a statistically significant odds ratio. The odds ratio was 6.26 in 2020, which is the highest since 2010. These alarming odds ratios highlight the importance of further interventions to improve the overall safety performance of construction workers.

According to Fang and Zhang (2012), detecting hazards is the first step in controlling them. Control responses to a recognized hazard include elimination, engineering, administration, and personal protective equipment (PPE). Clearly, PPE is the last resort in the hierarchy of control because the appropriate use of PPE depends on many factors, including worker attitude and overall safety culture and climate. Fatal and nonfatal injuries are a consistent challenge associated with inappropriate utilization of PPE (Hamid et al. 2008; Lette et al. 2018; Lestari et al. 2019). Several studies have reported that lack of PPE is the main cause of fall incidents (Chi et al. 2009; Lestari et al. 2019; Wong et al. 2021). According to Al-Bayati and York (2018), 85% of examined fatal fall incidents among Hispanic workers in the United States were associated with not using the required PPE. Similarly, Kang et al. (2017) found that 70% of all fall incidents involved a lack of PPE. Construction workers who do not use PPE are three times more likely to be injured than those who do (Lette et al., 2018). Melzner et al. (2013) suggest that wearing PPE contributes to a roughly 30% reduction in fall accidents. Thus, addressing the causes of inappropriate utilization of PPE should improve safety outcomes in construction workplaces (Martin et al., 2021). Safety management practices (e.g., disciplinary action, safety training, and effective safety communication) are critical contributors to the appropriate utilization of PPE among construction workers (Tam & Fung, 2012; Wong et al., 2020). The appropriate use of PPE is one of the most important safety factors in avoiding physical injuries (Ismail et al., 2012; Gunduz & Ahsan, 2018).

Safety supervision, in terms of resolving safety issues promptly and welcoming reports of safety issues, seems to be ineffective in increasing construction workers' use of PPE (Wong et al., 2020; Al-Bayati et al., 2019). Clearly, the role of safety culture (e.g., the actions of upper management and safety personnel) has a significant influence on worker behavior (Al-Bayati et al., 2019). For example, Mohajeri et al. (2021) reported that construction workers may rarely use PPE provided to them by contractors. Therefore, safety management practices that lead to strict safety policies are highly recommended and even welcomed by workers who prefer consistent enforcement of PPE use (Chen & Jin, 2015). On the other hand, safety management should also provide incentives to workers to encourage them to follow safety policies and address the physical discomfort that PPE may cause during various weather conditions, such as heat and high humidity (Man et al., 2021).

2. Research objectives and methodology

This study aims to reduce fatal and nonfatal injuries among construction workers. Accordingly, the objective of this study is to improve the industry's understanding of the factors that contribute to PPE non-compliance and improve the understanding of how to engineer and manage them. This objective will be met by answering the following research questions:

1. What are the factors that contribute to PPE non-compliance in construction workplaces?
2. What are the factors with predominant impact, and how can these factors be grouped based on similarity and prioritized based on importance to help decision makers use a separate strategy for each group?
3. What are the recommended proactive measures to engineer and manage the contributing factors to PPE non-compliance?

A 4-step research methodology was designed to answer the research questions: (1) a systematic literature review to identify factors that contribute to PPE non-compliance; (2) a questionnaire-based survey of subject-matter experts (SMEs) to rank the identified factors (i.e., a criticality assessment); (3) clustering factors into groups based on their rankings utilizing a K-means algorithm; and (4) a focus group study to validate the findings and develop a set of recommendations to engineer and manage the undesirable influence of identified factors. The following subsections discuss each step of the research methodology and its findings.

2.1. Literature review

A literature review is an effective method of gaining insight into a particular topic and evaluating what is currently known about the subject (Jesson et al., 2011; Fink, 2019). The authors employed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method to carry out the literature review. PRISMA is an evidence-based minimum set of items for reporting in systematic reviews and meta-analyses. The methodology of the research includes four major phases: identification, screening, eligibility, and inclusion, see Fig. 2.

The American Society of Civil Engineers (ASCE) online library and Science Direct databases were searched to identify relevant literature. The search was conducted with related keywords (e.g., personal protective equipment [PPE], construction accidents, non-use of PPE), focusing on published literature between 2002 and 2020. The first phase of the literature review resulted in 622 journal papers and conference proceedings. Accordingly, a literature screening was performed by skimming the articles' titles and abstracts, which resulted in 73 papers related to the research question. Accordingly, an eligibility evaluation was conducted using the 73 papers. Two members of the research team conducted the eligibility evaluation separately to avoid any potential errors. As a result, 19 related papers were included in the full literature review to identify the factors that contribute to PPE non-compliance among construction workers. Table 1 shows the 19 articles that have been included in the full literature review.

The literature review suggests that there are 16 factors that contribute to PPE non-compliance. Furthermore, a careful examination of the identified factors suggests that they can be categorized into the following four categories: PPE design factors, construction safety climate factors, construction safety culture factors, and other factors. Table 2 provides an example of each factor based on the reviewed literature. An explanation of the factor categorization follows:

- PPE design factors: Two factors are related to design shortcomings:

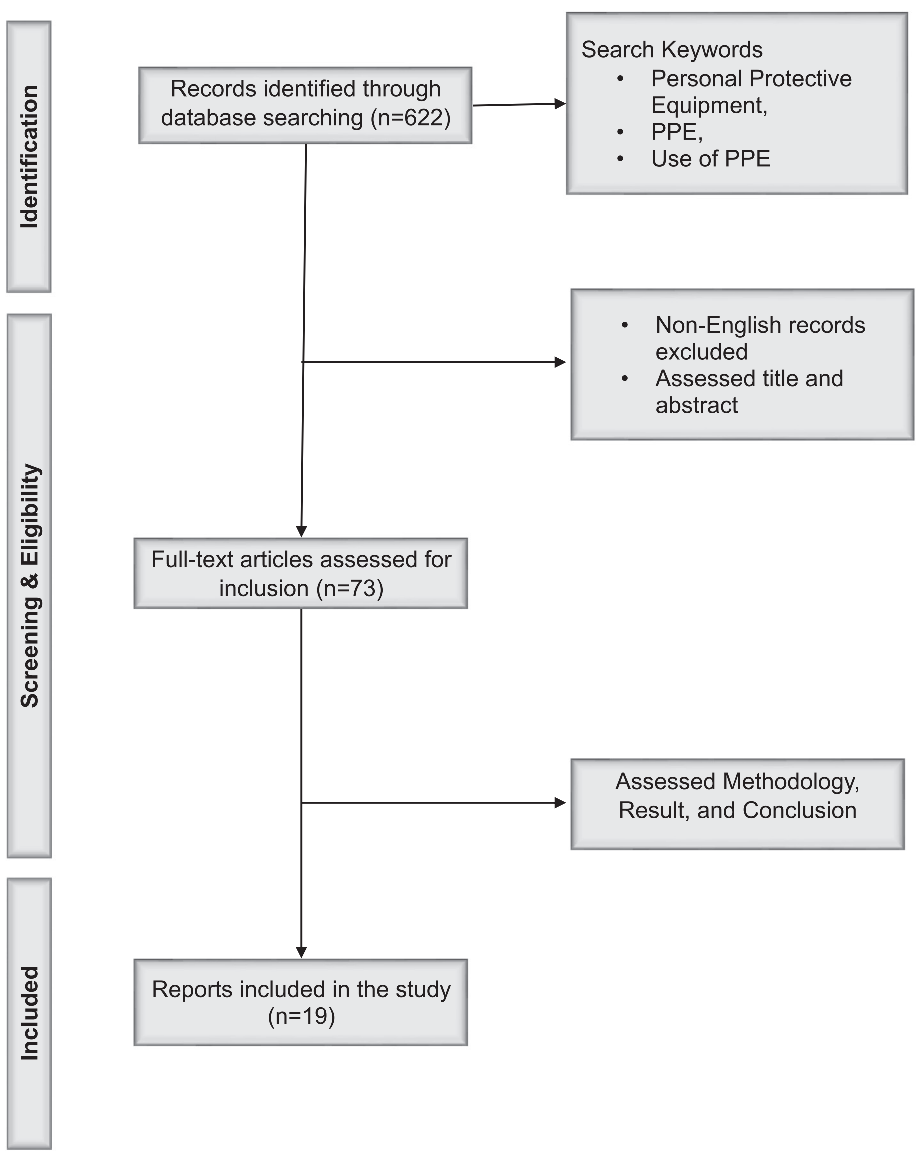

Fig. 2. The Literature Review Methodology.

Table 1
Articles Included in the Full Review.

Author(s) – Country	Article Title	Research Methods (Sample Size)
Wagner et al. (2013) – United States	Relationship between personal protective equipment, self-efficacy, and job satisfaction of women in the building trades	Survey (75)
Lombardi et al. (2009) – United States	Factors influencing worker use of personal protective eyewear	Focus group (51)
Man et al. (2017) – Hong Kong	Risk-taking behaviors of Hong Kong construction workers–A thematic study	Interview (40)
Dasandara and Dissanayake (2021) – Sri Lanka	Limiting reasons for the use of personal protective equipment among construction workers: Case studies in Sri Lanka	Interview (14)
Shokouhi et al. (2021) – Iran	Predicting the probability of occupational fall incidents: A Bayesian network model for the oil industry	Survey (1,000)
Menzel and Gutierrez (2010) – United States	Latino worker perceptions of construction risks	Focus group (30)
Arcury et al. (2014) – United States	Occupational safety beliefs among Latino residential roofing workers	Interviews (10)
Teran et al. (2015) – United States	Promoting adoption of fall prevention measures among Latino workers and residential contractors: Formative research findings	Survey (31)
Ulang et al. (2014) – Malaysia	Construction site workers' awareness on using safety equipment: Case study	Survey (60)
Wong et al. (2020) – Hong Kong	Critical factors for the use or non-use of personal protective equipment amongst construction workers	Interview (60)
Choudhry and Fang (2008) – Hong Kong	Why operatives engage in unsafe work behavior: Investigating factors on construction sites	Interviews (12)
Sehsah et al. (2020) – Egypt	Personal protective equipment (PPE) use and its relation to accidents among construction workers	Survey (382)
Izudi et al. (2017) – Uganda	Use of personal protective equipment among building construction workers in Kampala, Uganda	Survey (385)
Rafindadi et al. (2021) – Malaysia	Significant factors that influence the use and non-use of personal protective equipment (PPE) on construction sites—Supervisors' perspective	Survey (96)
Chi et al. (2005) – Taiwan	Accident patterns and prevention measures for fatal occupational falls in the construction industry	Case analysis (621)
Li et al. (2017) – Hong Kong	Investigation of the causality patterns of non-helmet use behavior of construction workers	Data analysis (43)
Martin et al. (2021) – United States	Exploring the role of PPE knowledge, attitude, and correct practices in safety outcomes on construction sites	Survey/interview (100)
Dale et al. (2021) – United States	Flow-down of safety from general contractors to subcontractors working on commercial construction projects	Survey (1,279)
Tam et al. (2004) – China	Identifying elements of poor construction safety management in China	Survey (60)

1) Poor quality, fit, and comfort
2) Lack of climate adaptation (e.g., workers do not want to wear poorly adapted PPE such as helmets or gloves in hot/cold climates)

- Construction safety climate factors: The construction safety climate category includes factors related to the actions of workers and frontline supervisors (Al-Bayati et al., 2019). For example, the perception that PPE use increases work effort and time requirements and inadequate safety supervision are related to field workers and frontline supervisors. Factors within this category not only impact the individuals who conduct unsafe actions but also discourage other workers from using safety equipment, which compromises overall safety performance. Similarly, frontline supervisors who fail to emphasize and enforce the use of safety equipment also contribute to PPE non-compliance. There are seven factors within this category:
  1) Workers believe that PPE increases work time
  2) Workers believe that PPE increases work effort
  3) Workers believe that PPE increases restrictions
  4) Inadequate safety supervision: Safety supervision is necessary to enforce compliance with safe work practices. Otherwise, workers may display a negligent attitude and disregard safety rules (Martin et al., 2021)
  5) Peer pressure
  6) Poor worker risk perception [i.e., poor worker assessments of the risks they are exposed to (Wong et al., 2020)]
  7) Performance pressure
- Construction safety culture factors: The corporate construction safety culture category includes factors that are related to the actions of upper management and safety personnel, such as lack of safety training and upper management support (Al-Bayati et al., 2019). It is worth noting that there are three dimensions of safety culture: corporate, psychological, and behavioral (Zou & Sunindijo, 2015). An explanation of these dimensions is beyond the scope of this paper. However, interested readers may refer to Al-Bayati et al. (2019) and Zou and Sunindijo (2015), where this topic is discussed in more detail. Clearly, firm size contributes to a lack of safety rules and policies as well as a lack of PPE availability and accessibility. Al-Bayati (2021a) suggested that there is a statistically significant positive correlation between firm size and construction safety culture because smaller construction firms have limited resources to create and maintain adequate safety and health policies. There are four factors within this category:
  1) Lack of safety training
  2) Lack of management support
  3) Lack of safety rules and regulations
  4) Lack of PPE availability and accessibility
- Other factors: There are three factors within this category: (1) unstable employment status (temporary and seasonal employment), (2) somatic health effects, and (3) cultural and language barriers. Temporary workers who are hired and paid by a staffing agency are at increased risk of work-related injury and illness (Occupational Safety and Health Administration (OSHA, 2014). Some workers cannot wear PPE due to physical and mental stress, especially in confined or poorly ventilated areas. On the other hand, it has been suggested that cultural and language barriers contribute to higher fatality rates among ethnic minority construction workers (e.g., the Hispanic workforce in the United States; (Thompson & Siddiqi, 2007; McGlothlin et al., 2009; Al-Bayati et al., 2017). Therefore, training modules designed to overcome cultural and language barriers should be employed (Al-Bayati, 2019). Hispanic workers do not always receive the necessary PPE due to their employment status,

Table 2
Causes of personal protective equipment (PPE) non-compliance.

	Factors	Factor Explanation Based on the Reviewed Articles	References
PPE Design Factors	F01. Poor quality, fit, and comfort	• Gender-specific or smaller/larger sized PPE (e.g., gloves) is not available. • Lack of comfort/fit and fogging and scratching of eyewear may inhibit their usage. • Distortion and clarity problems associated with eyewear may result in somatic effects, such as headaches, dizziness, or nausea. • PPE is uncomfortable or ill-fitting when worn during all necessary working hours. • PPE is not stylish.	Lombardi et al. (2009); Wagner et al. (2013); Man et al. (2017); Wong et al. (2020); Arcury et al. (2014); Wong et al. (2020); Sehsah et al. (2020); Rafindadi et al. (2021); Shokouhi et al. (2021)
	F02. Lack of climate adaptation	• Workers reported discomfort wearing poorly adapted PPE in hot/cold climates.	Dasandara and Dissanayake (2021)
Safety Climate Factors	F03. Workers believe that PPE increases work time	• Workers think PPE delays their work because the use of some PPE items (such as harnesses) reduces mobility (i.e., perceived as an impediment to productivity) • Workers want to complete tasks in the shortest time possible; thus, they often fail to take safety measures that require considerable time. • Workers believe that contractors do not want them to use PPE because the PPE prevents them from working faster. • Interviewees (roofers) believe that they can work faster with no PPE.	Wong et al. (2020); Arcury et al. (2014); Man et al. (2017)
	F04. Workers believe that PPE increases work effort	• Workers believe that safety measures require significant effort. For example, some workers prefer to use ladders that do not match safety standards instead of establishing a working platform when working in high areas because they feel that establishing a platform requires too much effort.	Wong et al. (2020); Arcury et al. (2014); Man et al. (2017)
	F05. Workers believe that PPE increases restrictions	• Working in a limited space is inconvenient with the use of a safety helmet because head movement is restricted. • Some workers think there is limited workspace for them to use PPE. • Workers report that PPE restricts movement, becomes tangled, is heavy, and impedes communication. Workers feel that these restrictions in range of movement are hazards, and they report feeling less safe wearing PPE because it makes their movements awkward.	Wong et al. (2020); Sehsah et al. (2020); Rafindadi et al. (2021)
	F06. Inadequate safety supervision	• Supervisors try to maintain good relationships with workers to complete projects on time and as expected. Therefore, management purposely tolerates the situation without insisting on PPE use. • Workers remove PPE when managers are not in sight. It is obvious in this context that workers are motivated to use PPE only through transactional leadership. • There is a lack of involvement of external responsible parties in monitoring safety supervision at sites.	Dasandara and Dissanayake (2021); Ulang et al. (2014); Choudhry and Fang (2008); Rafindadi et al. (2021); Martin et al. (2021)
	F07. Peer pressure	• Some co-workers tease and make fun of those who choose to use PPE. • Some workers want to prove they are "tough guys" and are not scared of getting hurt.	Choudhry and Fang (2008); Wong et al. (2020); Arcury et al. (2014); Menzel and Gutierrez (2010); Man et al. (2017); Lombardi et al. (2009)
	F08. Poor risk perception	• Some experienced workers rely on their experience, believing that they don't need PPE; some young workers often see work as an adventure and are overconfident. • Some workers think the chance of accidents is small. • Some workers do not accept the concept that they should be motivated to wear PPE for their own safety. They view PPE only as a job requirement. • Workers state that their risk-taking behaviors, such as smoking at work and not using a safety harness, have become habits. Although the construction workers know that these behaviors are dangerous, they still perform such behaviors out of repetition and habit rather than conscious deliberation of costs and benefits.	Lombardi et al. (2009); Man et al. (2017); Dasandara and Dissanayake (2021); Teran et al. (2015); Rafindadi et al. (2021); Li et al. (2017)
	F09. Performance pressure	• Workers state that productivity bonuses have led them to achieve higher production at the expense of safety. • Workers report experiencing performance pressure from their supervisors.	Rafindadi et al. (2021); Choudhry and Fang (2008); Arcury et al. (2014)
Safety Culture Factors	F10. Lack of		Lombardi et al. (2009); Dasandara and Dissanayake

Table 2 (*continued*)

	Factors	Factor Explanation Based on the Reviewed Articles	References
	safety training	• Most workers without safety training report working either for themselves or for small companies with no formal safety training program. Reported use of PPE is lowest among these workers. • There is a lack of safety education and training on the appropriate use of PPE. • There is a lack of worker knowledge of all applicable safety laws at construction sites. • Workers do not know how to use PPE. • Some workers are uneducated. They cannot read and understand safety material (illiteracy).	(2021); Teran et al. (2015); Ulang et al. (2014); Choudhry and Fang (2008); Sehsah et al. (2020); Izudi et al. (2017); Rafindadi et al. (2021); Chi et al. (2005); Li et al. (2017); Martin et al. (2021)
	F11. Lack of management support	• Management commitment to safety for better safety policies and procedures and effective safety training is lacking. • No one is enforcing labor laws or ensuring contractors follow regulations. This lack of enforcement allows contractors to operate with an emphasis solely on production, without feeling any pressure to follow safety guidelines or labor laws in general. • Good practices, such as the use of PPE while working, are not rewarded or appreciated by management. • Management makes inadequate efforts to provide adequate PPE.	Tam et al. (2004); Dale et al. (2021); Rafindadi et al. (2021); Choudhry and Fang (2008); Ulang et al. (2014); Teran et al. (2015); Arcury et al. (2014); Lombardi et al. (2009)
	F12. Lack of safety rules and policies	• There are no specific rules and regulations in place with regard to the use of PPE, especially for small and medium-sized enterprises (SMEs). They are in a flexible mode in terms of following rules and regulations when compared to large-scale construction organizations. • Pre-task evaluations are not always performed. As a result, there is a severe lack of effective enforcement, including safety inspections, risk assessments, and accident reporting.	Teran et al. (2015); Rafindadi et al. (2021); Martin et al. (2021); Dale et al. (2021)
	F13. Lack of PPE availability and accessibility	• Small contractors are often not equipped to work on hazardous sites because they lack proper PPE, yet they engage in projects that require such equipment. • Some workers cannot always get PPE when they need it. • Even though it is a violation of Occupational Safety and Health Administration PPE standards, some workers report being required to purchase their own PPE. • Some workers perceive that their boss (supervisor) does not have the money to buy PPE for workers, so they fail to use PPE.	Tam et al. (2004); Rafindadi et al. (2021); Sehsah et al. (2020); Wong et al. (2020); Teran et al. (2015); Shokouhi et al. (2021); Dasandara and Dissanayake (2021); Man et al. (2017); Lombardi et al. (2009)
Other Factors	F 14. Unstable employment status	• Temporary and casual workers are less likely to use PPE than permanently employed workers. • Undocumented workers cannot ask their employers for PPE because they are afraid of reprisal from employers if any safety concessions are requested, and they do not complain even when injuries occur because they need consistent work to support their families.	Dasandara and Dissanayake (2021); Arcury et al. (2014); Teran et al. (2015); Ulang et al. (2014); Izudi et al. (2017)
	F15. Somatic health effects	• Wearing PPE causes stress in hot, sunny, confined, and/or poorly ventilated areas. • Poor health conditions lead some workers to abandon the use of PPE.	Lombardi et al. (2009); Dasandara and Dissanayake (2021); Sehsah et al. (2020)
	F16. Cultural and language barriers	• The participants (e.g., Latino workers) did not insist that supervisors provide safety gear because they felt intimidated by communicating with a person in authority (a traditional Latino value). • Different lifestyles from different cultures have discouraged the use of PPE.	Menzel and Gutierrez (2010); Dasandara and Dissanayake (2021)

which forces them to value job security over speaking up about safety issues (Grzywacz et al., 2012; Shrestha & Menzel, 2014; Al-Bayati et al., 2017).

2.2. Subject-matter experts (SMEs) – criticality assessment

This step aims to perform a criticality assessment (i.e., factor ranking) of the 16 factors identified in the literature review. Within this study context, the SMEs are construction practitioners with at least one year of experience. To improve the accuracy of the criticality assessment, fuzzy set theory (FS) was applied. FS is a robust system where no precise inputs are required since it can deal with subjective and imprecise judgments. FS was used in this study to quantify the verbal opinions and subjective judgments of the SMEs who participated in the study. A fuzzy number $P(\Theta)$ refers to a continuous set of possible values, where each value has a membership function that varies between 0 and 1. Typically, $P(\Theta)$ is represented as triangular, Gaussian, or trapezoidal fuzzy numbers to convert verbal/linguistic expressions by experts into fuzzy numbers. According to Li et al. (2012), triangular fuzzy numbers provide more precise descriptions and accurate results than the other representations. A triangular $P(\Theta)$ includes three values, where P

$(\Theta) \cong (\theta_1, \theta_2, \theta_3)$, where θ_2 has the membership function of 1, and the values between θ_2 and θ_1 or θ_3 have membership functions between 1 and 0. Values less than θ_1 or greater than θ_3 have a membership function of zero (Emrouznejad & Ho, 2017).

The triangular fuzzy numbers were selected by including three components for each linguistic term (i.e., fuzzification). Fig. 3 shows a graphical representation of the scaled triangles representing the linguistic terms to be assigned by each expert. The experts were asked to select the contribution level of each factor affecting PPE non-compliance in construction workplaces using linguistic terms (i.e., none, low, moderate, high, absolute).

The assessments of experts were combined using the linear opinion pool (LOP), where $P_i(\theta)$ is a fuzzy triangular number [denoted by $P(\theta) = (a, b, c)$] assigned by the experts, and w_i is the percentage of experts who assigned $P_i(\theta)$.

$$P(\theta) \cong \sum_{i=0}^{n} [w_i \otimes P_i(\theta)] \quad (2)$$

The fuzzy triangular number $P(\theta)$ resulting from Equation (2) can be represented by a crisp number *Val (θ)* using Equations (3) and (4) as follows:

$$Val(\theta) = \int_0^1 Average(\theta_\alpha).d\alpha \quad (3)$$

Where $\theta_\alpha = \{x|F(x) \geq \alpha\}$ is the α-level of θ. The generalized formulation of a crisp number (i.e., defuzzification) *Val (θ)* can be achieved as shown in Equation (3) below:

$$Val(\theta) = \frac{\frac{1}{2}\int_0^1 [(b-a)\times\alpha + a + c - (c-b)\times\alpha]}{\int_0^1 d\alpha} = \frac{a+2b+c}{4} \quad (4)$$

Accordingly, a survey was designed and submitted to the Human Subject Institutional Review Board (HSIRB) at Lawrence Technological University for review and approval. The survey questions are included in Table S1 of the Supplemental Materials. After approval, the invitations to participate were sent utilizing a convenience sample, which is a widespread research methodology in construction research due to the infeasibility of other sampling plans, such as probability-based sampling. The survey was administered between February and April 2022, and 184 valid responses were collected. A response is considered valid when the respondent takes more than 13 minutes to complete their response and does not provide any gibberish answers to open-ended questions. Thirteen minutes is the median time needed to complete the first 50 valid responses. The authors chose the median time instead of the average time because it is not severely impacted by delayed responses. In addition, responses from participants with less than one year of experience were removed. The main goal of these filters is to objectively remove low quality responses. Participants were presented with the study description and consent form, which led to the questionnaire only after the respondent voluntarily agreed to participate.

The participants represent diverse backgrounds of education, work experience, and firm size. Most of the participants (62.5%) had more than 10 years of experience, followed by participants with 6–10 years of experience (23.4%) and 1–5 years of experience (14.1%). The job descriptions of the participants fall within the following categories: construction workers (28.3%), construction supervisors (25.8%), safety personnel (15.8%), upper management (31.5%), and other (8.7%). The educational degrees of the participants fall within the following categories: Department of Labor registered apprenticeship (6; 3.3%), high school diploma (46, 25%), community college (31, 16.8%), Bachelor of Science or equivalent (75, 40.8%), master's degree or higher (17, 9.2%), and others (9, 4.9%). The participants' firm sizes in terms of the number of employees fall within the following categories: less than 10 employees (26, 14.1%), 10–50 employees (49; 26.6%), 51–100 employees (31; 16.8%), 101–250 employees (39; 21.2%), and more than 250 employees (39; 21.2%).

The experts assessed PPE factors using verbal expressions. This assessment was then converted into fuzzy numbers using Fig. 3 to model the inherited uncertainty from subjective input, then aggregated using Equation (2). For instance, for factor F1 "Poor Quality, Fit, and Comfort," 14 experts of 184 (7.6%) selected "absolute" associated with the fuzzy number of (0.75,1.00,1.00), 40 experts (21.7%) selected "high" associated with the fuzzy number of (0.50,0.75,1.00), 90 experts (48.9%) selected "moderate" associated with the fuzzy number of (0.25,0.50,0.75), 34 experts (18.4%) selected "low" associated with the fuzzy number of ((0.00,0.25,0.50), and 6 experts (3.2%) selected "none" associated with the fuzzy number of (0.00,0.00,0.25). The aggregated fuzzy number $P(\theta)$ for F1 is calculated as (0.28,0.52,0.76) using Equation (2); where, 0.076 * 0.75 + 0.217 * 0.5 + 0.489*0.25 + 0.184*0.00 + 0.032*0.00 = 0.28; 0.076 * 1.0 + 0.217 * 0.75 + 0.489*0.50 + 0.184*0.25 + 0.032*0.00 = 0.52; and 0.076 * 1.0 + 0.217 * 1.0 + 0.489*0.75 + 0.184*0.50 + 0.032*0.25 = 0.76. This result of the factor F1 indicates that, on the fuzzy scale shown in Fig. 3, the most likely value of P(θ) is 0.52, the upper likely value of P(θ) is 0.76, and the lower likely value of P(θ) is 0.28. The resulting values for F1 are

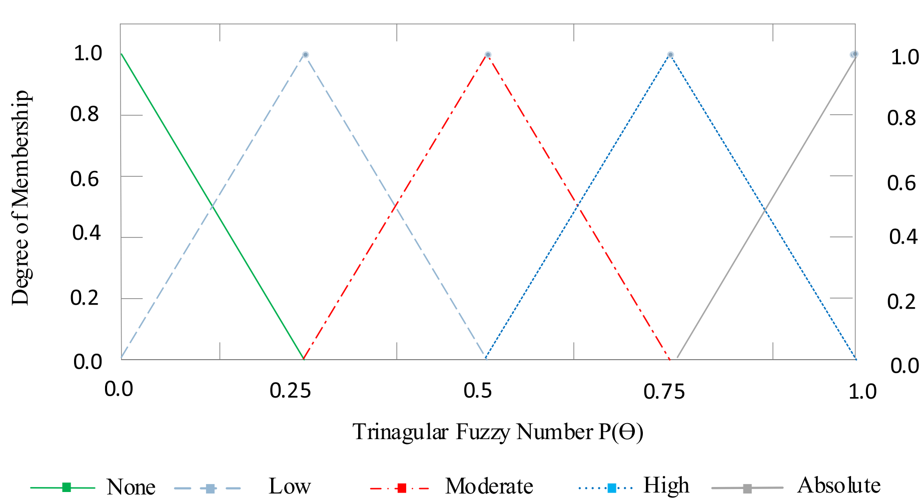

Fig. 3. Fuzzy Numbers Corresponding to Linguistic Terms.

Table 3
The Average Fuzzy Scores of the Study Factors.

Factor	Average Score	Standard Deviation
F06. Inadequate Safety Supervision	0.5625	0.2381
F08. Poor Risk Perception	0.5554	0.2325
F02. Lack of Climate Adaptation	0.5428	0.2037
F01. Poor Quality, Fit, and Comfort	0.5272	0.2131
F05. PPE Increases Restrictions	0.5187	0.2161
F15. Somatic Health Effects	0.5119	0.2402
F04. PPE Increases Work Effort	0.5014	0.2208
F10. Lack of Safety Training	0.4776	0.2513
F03. PPE Increases Work Time	0.4721	0.2323
F09. Performance Pressure	0.4575	0.2510
F14. Unstable Employment Status	0.4433	0.2474
F11. Lack of Management Support	0.4416	0.2547
F13. Lack of PPE Availability and Accessibility	0.4327	0.2504
F12. Lack of Safety Rules and Regulations	0.4263	0.2533
F16. Cultural and Language Barriers	0.3933	0.2442
F07. Peer Pressure	0.3923	0.2494

fuzzy triangular numbers, represented by $P(\theta) \cong (a, b, c)$. However, it is necessary to transform fuzzy numbers into crisp values for the purpose of factor evaluation. To achieve this goal, the defuzzification process was applied. The fuzzy triangular numbers $P(\theta)$ have been represented by crisp numbers Val (θ) using Equation (4). For example, for calculating the crisp number Val (Θ) for the factor F1"Poor Quality, Fit, and Comfort" with the value of a = 0.28, b = 0.52, and c = 0.76, the resulting crisp Val (Θ) is 0.527. Table 3 shows the criticality levels of the 16 factors. Table 3 shows the average crisp number of each factor. The factors are sorted from the highest crisp score to the lowest. Table 4 shows a sample of the defuzzification of 10 variable expressions that survey participants provided for factor 1.

2.3. K-means Clustering – Prioritizing Groups

Clustering is a method of identifying similar groups based on similarities in attributes, features, and other characteristics. Within this study context, clustering aims to arrange similar factors in terms of score values (i.e., defuzzification crisp numbers) into groups. This method helps decision makers better manage critical factors by prioritizing the allocation of any available mitigation resources (e.g., funding and safety personnel). Factor clustering enables decision makers to consider factors with predominant impact. Allocating factors into clusters also helps decision makers use a separate strategy for each group of factors based on the importance of those factors.

Several algorithms could be used for clustering. The most well-known algorithm types are connectivity, distribution, and centroid model (i.e., K-means algorithm). The K-means algorithm is used in this study because the assessed factors do not follow a specific distribution that can be used for clustering (Oskouie et al., 2017). The K-means algorithm is operated based on the notion of similarity that is derived from the closeness of a data point to the centroid of the clusters. K-means is an iterative algorithm that identifies and classifies similar groups of factors based on criticality. It includes two steps to identify the number of clusters and the factors that should be included within each cluster. The optimal number of clusters (K) is determined in the first step. The second step is clustering iterations, where each factor is allocated to the best fit cluster.

Techniques such as the elbow method and silhouette are typically used to determine K. It is noted that compared to the elbow method, the silhouette score is less prone to error as it uses a similarity measure that is based on the distance of the data points from their own clusters and the comparative distance to other clusters. Additionally, the elbow method uses only the sum of squared errors as the comparison factor. Thus, the silhouette score method is used to determine the number of clusters. The 16 factors were grouped using iterative k values ranging from 2 to 10 clusters. Equation (5) was used to calculate the silhouette method's similarity measure (S). The value of S range from −1 to 1, where a value near 1 indicates a well-matched cluster. Accordingly, the k value that produces the highest average silhouette score is the most optimal clustering number.

$$S = \frac{b - a}{\max(a, b)} \quad (5)$$

Where a represents the mean intra-cluster distance, and b represents the distance between a factor and the nearest cluster to which the factor does not belong.

The second step is clustering iterations. This step includes randomly assigning each factor to a cluster, computing cluster centroids, assigning the factor to the closest cluster centroid, and recomputing cluster centroids. It is worth mentioning that the computations and processing of these two steps are performed automatically by encoding the K-means algorithm into the R software. The optimal number of clusters must correspond to the maximum silhouette score (Yuan & Yang, 2019). Fig. 4 shows that the silhouette scores are close to each other between 2 and 6 clusters but are not identical. The maximum silhouette score is 0.62, which corresponds to five clusters. Accordingly, the 16 factors were assigned to 5 clusters, see Table 5.

2.4. Focus group study

Focus group meetings should be used to further understand and validate survey findings when using a non-probability survey sample. It is crucial to gather data utilizing a mixed methods methodology (e.g., a survey and focus group study) to gain confidence in the findings (Abowitz & Toole, 2010; Al-Bayati et al., 2017). According to Liamputtong (2011), focus group interviews gather a group of people to discuss a particular subject. Focus group inter-

Table 4
Example of Defuzzification Process.

Experts	Verbal Expression	Fuzzy number	Min	Mean	Max	Crisp Number
1	Moderate	(0.25,0.50,0.75)	0.25	0.5	0.75	0.5
2	Moderate	(0.25,0.50,0.75)	0.25	0.5	0.75	0.5
3	High	(0.50,0.75,1.00)	0.5	0.75	1	0.75
4	Moderate	(0.25,0.50,0.75)	0.25	0.5	0.75	0.5
5	Moderate	(0.25,0.50,0.75)	0.25	0.5	0.75	0.5
6	High	(0.50,0.75,1.00)	0.5	0.75	1	0.75
7	None	(0.00,0.00,0.25)	0	0	0.25	0.0625
8	Moderate	(0.25,0.50,0.75)	0.25	0.5	0.75	0.5
9	High	(0.50,0.75,1.00)	0.5	0.75	1	0.75
10	Moderate	(0.25,0.50,0.75)	0.25	0.5	0.75	0.5

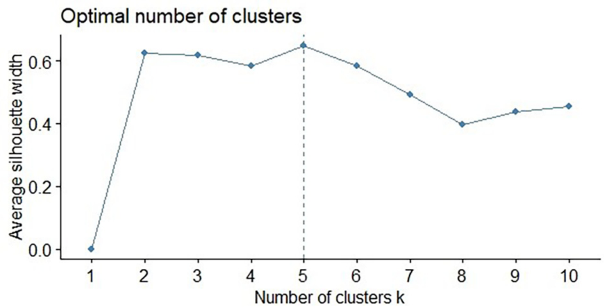

Fig. 4. The Optimal Number of Clusters.

views have unique features, such as enabling in-depth discussion and allowing interaction among participants. Methodologically, focus group studies engage the participants in a dynamic discussion for 1 to 2 hours to collect a range of participant opinions and reduce areas of misunderstanding.

Accordingly, focus groups were conducted by the research team to (1) validate the ranking of identified factors, (2) suggest proactive measures to effectively manage them, and (3) explore other potential contributing factors to PPE non-compliance. Two focus group meetings were conducted with four participants per session to enable in-depth discussion and allow interaction among participants. After the second session, the authors decided not to conduct additional focus group sessions due to the similarities between the results of previous sessions. The focus group study should come to an end when there is no new information collected; as a result, continuing interviews becomes pointless (Liamputtong, 2011). The two meetings took place in Southfield, MI, in May 2022.

Focus group sessions started with a presentation illustrating the following: construction workforce fatalities over a period of 10 years, the contribution of PPE non-compliance to these fatalities, and the survey findings. This presentation was designed to increase awareness among participants and to communicate the study objectives to motivate critical and in-depth discussion. During the discussion, the participants were also asked to complete a survey to record their agreement or disagreement with the survey findings and to suggest proactive measures to improve overall PPE compliance.

The average years of experience of participants within the construction industry was 15.6 years (SD = 13), and within the construction safety profession was 12 years (SD = 9). Based on a review of the criticality clusters, all participants suggested that the lack of safety training and lack of management support should be moved to the high criticality cluster. This suggestion is justifiable because actions of upper management and safety personnel significantly influence the behavior of field personnel, as suggested by Al-Bayati (2021b). Table 5 shows the clusters and their corresponding factors based on the survey findings as well as feedback and suggestions provided by focus group participants. Suggesting proactive measures is critical to eliminate or reduce the influence of the identified factors. Table 6 summarizes the proactive measures suggested by focus group participants.

Finally, the participants were asked to highlight other factors that may contribute to PPE non-compliance. Participants emphasized the contribution of financial constraints in terms of budget availability to purchase adequate PPE and hire the required number of qualified safety personnel. Participants also emphasized the difficulties of hiring and keeping enough safety personnel on-site to supervise and enforce PPE regulations due to financial constraints, especially among smaller construction firms. In addition, participants agreed that the client has an influence on overall safety performance. For example, one of the participants stated the following:

> "I used to work for a large concrete company, and one of my first jobs with them was on a nuclear facility. My first experience with this company, safety is very, very tight on a nuclear facility. However, the same company, same guys, literally, we all got shipped to a different site under a different client where the safety was not the focus; our safety program and performance completely changed."

Table 5
Criticality Assessment Clusters.

Factor	K-cluster	Criticality Level
F06. Inadequate Safety Supervision	1	High
F08. Poor Risk Perception		
F02. Lack of Climate Adaptation		
F10. Lack of Safety Training*		
F11. Lack of Management Support**		
F01. Poor Quality, Fit, and Comfort	2	Moderate to High
F05. PPE Increases Restrictions		
F15. Somatic Health Effects		
F04. PPE Increases Work Effort		
F03. PPE Increases Work Time	3	Moderate
F09. Performance Pressure		
F14. Unstable Employment Status	4	Moderate to Low
F13. Lack of PPE Availability and Accessibility		
F12. Lack of Safety Rules and Regulations		
F16. Cultural and Language Barriers	5	Low
F07. Peer Pressure		

* F10 was moved to the high criticality level from the moderate criticality level based on focus group recommendations.
** F11 was moved to the high criticality level from the moderate to low criticality level based on focus group recommendations.

3. Theoretical and practical contributions

PPE non-compliance places construction workers who do not use PPE and their co-workers at risk; however, the blame for this action does not fall on workers' unsafe behavior alone. Unsafe behavior should be considered the direct cause of incidents and is a result of other factors such as lack of upper management support, safety personnel competence, and inadequate safety supervision (i.e., root causes). There are, in fact, many factors that contribute to this unsafe behavior of not using or inappropriately using PPE, as this study reveals. Identifying and prioritizing the contributing factors is vital to effectively engineer and manage construction safety and reduce fatal and nonfatal injuries.

On a theoretical level, this study will eventually contribute to human error theories and behavior models. Human error frameworks were originally developed and tested as a tool for investigating and analyzing the human causes (i.e., errors) of incidents (Garrett & Teizer, 2009). Human errors should be viewed as opportunities to investigate and identify the chain of events that led to the error. The accident-causing theory suggests that a series of coupled unsafe events leads to an incident (Liu, 2020). Thus, breaking the coupling relationship between unsafe events is crucial to prevent an incident. Human error theories should be embedded in behavior models that do not blame unsafe behavior alone, but workplace factors as well (Al-Bayati et al., 2021). In addition, human limitations should be considered. Upper management's commitment and safety personnel competency significantly contribute to field personnel's safety behavior (Al-Bayati et al., 2019). According to Choudhry and Fang (2008), human error and behavioral theories should stress the need for enhanced engineering and management techniques to deliver better-designed tasks and tools, while addressing human limitations (e.g., physical and psychological capabilities). Thus, the widely accepted suggestion

Table 6
Proactive Measures Suggested by Focus Group Participants.

Cluster	ID	Proactive Measures
Cluster 1 (High Criticality)	F06	• Encouraging, measuring, and monitoring frontline supervisor accountability • Providing safety resources (e.g., designated site safety representatives) and fostering clear and professional communication between frontline supervisors and workers
	F08	• Emphasizing the stakes involved in non-compliance with PPE • Enhancing the critical thinking of workers through interactive risk perception training (dialoguing with workers about "what-if" and worst-case scenarios)
	F02	• Improving PPE supply and providing specialized training and resources for wearing PPE in adverse weather conditions • Providing cooling and heating stations for workers operating in intense weather conditions
	F10	• Providing training at the same time that PPE is provided, to all new hires, and yearly refresher training • Improving management support for educational and outreach programs
	F11	• Emphasizing the reputational and financial costs of accidents due to PPE non-compliance • Increasing leadership involvement, visibility (e.g., bringing management into the safety program to demonstrate PPE use), and accountability
Cluster 2 (Moderate to High Criticality)	F01	• Improving the supply of PPE (different styles and sizes should be available) • Improving PPE training and gaining worker input on PPE fit and comfort
	F05	• Gaining worker input on potential restrictions and addressing them • Conducting case-by-case evaluations to reach a resolution
	F15	• Exploring PPE alternatives for individuals with health problems and employing case-by-case decision-making • Raising worker awareness of the possible relationships between PPE use and certain health conditions
	F04	• Getting employee feedback on PPE options that will not adversely affect effort and encouraging workers to suggest PPE alternatives • Showing documentation of the costs of accidents and injuries associated with failure to use PPE
Cluster 3 (Moderate Criticality)	F03	• Providing explanations and examples of the time costs of incidents and ensuring adequate time for PPE use and installation • Letting workers know they will be evaluated more favorably if they work safely than if they work quickly but unsafely
	F09	• Emphasizing the costs of safety incidents associated with PPE non-compliance • Ensuring that field leadership understands that safety cannot be sacrificed and providing rewards and incentives for good safety performance
Cluster 4 (Moderate to Low Criticality)	F14	• Ensuring that all employees are trained to the same standard • Developing a strong temporary worker program and partnership with staffing agencies
	F13	• Improving PPE availability by introducing technologies such as PPE vending machines and QR codes to make PPE distribution more efficient • Improve PPE funding by obtaining available grants and allocating PPE pay items within the contracts of smaller subcontractors
	F12	• Ensuring safety programs are up to date, post safety programs at all job sites, and communicate OSHA PPE requirements • Enforcing PPE compliance and creating a sliding scale for safety performance penalties
Cluster 5 (Low Criticality)	F16	• Implementing multi-language literature and training (e.g., using images and pictures in training) • Fostering an inclusive workplace culture
	F07	• Encouraging and rewarding positive peer pressure around PPE use • Discouraging negative peer pressure via effective field monitoring and education

that a high proportion of construction incidents are a result of unsafe behavior (i.e., human error) should be reconsidered. Unsafe behavior should be deemed as the direct cause of incidents, and it is a result of root causes such as lack of upper management support, safety personnel incompetence, and inadequate safety supervision. Addressing the root causes is critical to reduce unsafe behavior.

On the practical level, this study will eventually contribute to reducing fatal and nonfatal incidents among construction workers. The study helps decision makers better manage and engineer critical contributing factors to PPE non-compliance by prioritizing the allocation of available resources (e.g., safety allocated funds and competent safety personnel). Specifically, factors clustering enables decision makers to focus on the most critical factors by utilizing provided proactive measures. The suggested proactive measures call for actions from all stakeholders (i.e., PPE designers and manufacturers, upper management, safety personnel, frontline supervisors, and workers). The proactive measures focus on leadership and frontline supervisor accountability; safety resources, including adequate PPE supply; communication; safety policies; specialized training for wearing PPE in adverse conditions; worker attitudes; gaining worker input on PPE; leadership involvement and visibility; emphasizing the financial and reputational stakes of PPE non-compliance; PPE alternatives for individuals with health problems; case-by-case decision making; and multilanguage literature and training, including pictures. These areas of focus fall within upper management and safety personnel's control. Accordingly, the overall study findings suggest that the root causes of PPE non-compliance are embedded within the actions of upper management and safety personnel. The top three most important proactive measures for PPE compliance are to encourage, measure, and monitor frontline accountability; to emphasize the stakes associated with not using PPE; and to provide more resources to field personnel and smaller construction firms. Specific suggestions for these measures include involving frontline supervisors and workers in decision making and buy-in for safety rules and investments in safety improvements, providing real world examples of the physical and financial consequences of PPE non-compliance, and providing more training and better PPE. Emphasizing the stakes of non-compliance include reminding workers that they have families waiting for them at home, having one-on-one conversations with workers about the potential consequences of their violations, showing images of and telling stories about previous incidents, and highlighting the costs of incidents (in terms of financial and time/productivity loss) to both workers and frontline supervisors.

The limited resources available for smaller construction firms, especially residential construction firms, was thoroughly discussed during the focus group sessions. Specific suggestions for providing more resources include seeking out and consulting with trade-specialized safety experts, developing partnerships, seeking grants, and providing a variety of specialized equipment by owners and general contractors, such as adjustable PPE, PPE vending machines, and worker-specific QR codes to monitor equipment distribution. These suggestions will help improve the noticeable low levels of safety culture (i.e., low upper management commitment and low safety personnel competency) that was found by Al-Bayati (2021a). On the other hand, project owners and general contractors should consider allocating a dollar amount for safety programs when hiring smaller construction firms and including a safety plan in the contract selection criteria. Owners and general contractors should realize that the cost of safety programs and equipment is hidden within project overhead. Thus, allocating a dollar amount for it in the contract is a good practice to ensure a common understanding of the safety management team and plan. Better safety management improves overall project delivery in terms of budget, time, and quality. Safety issues can lead to work interruptions and undesirable press. Thus, it is to the owner's benefit to allocate funds for safety.

Finally, providing rewards and incentives for good safety performance was suggested to address the undesirable influence of performance pressure (being on time within the project schedule). This suggestion aims to integrate safety performance into overall firm operations. Safety management is often viewed as a non-core business obligation to prevent OSHA fines (Ladewski & Al-Bayati, 2019). Thus, integrating safety into business functioning is crucial. Construction practitioners should be aware that OSHA discourages rewards and incentives that may lead to non-reporting of injuries and near misses. Therefore, it is recommended to provide incentives and rewards for employees who frequently report near misses and unsafe conditions and behavior, as well as those who actively participate in safety training and safety talks.

4. Limitations

The results reported in this paper should be utilized in light of two main limitations. First, the criticality assessment employs a cross-sectional survey. Although the study findings are sufficient to draw inferences, as they were validated utilizing focus groups, there is a need for field observations to further validate the study findings. Specifically, the low score of the peer pressure factor could be a result of the survey methodology. Participants who are asked about the influence of peer pressure may tend to report low scores. The low scoring could be explained by a phenomenon termed "social desirability," which is the tendency to respond to questions in the manner that is likely to be most socially approved (Davis, 2010). People tend to reject that their peers may influence their behavior. Furthermore, the social proof phenomenon should also be assessed, which is different from peer pressure in that it is self-motivated. Within this study context, the social proof suggests that if lots of workers are not wearing or inappropriately wearing PPE, then other workers believe that there is a good reason for such behavior and will follow the same behavior. Social proof was first assessed and discussed by Milgram et al. (1969). Second, the causal interrelations among the 16 factors were not assessed. It is anticipated that some factors are a result of one or more of the others. Thus, it is recommended that future research focus on the causal interrelations between the identified factors.

5. Conclusion

This study delivers a comprehensive review of the factors that contribute to PPE non-compliance on construction worksites. This study included three phases: (1) identification of PPE non-compliance factors, (2) criticality risk assessment, and (3) findings validation and practical recommendations. Accordingly, 16 factors were identified through an extensive literature review. The identified factors were grouped into four categories (design factors, safety climate factors, safety culture factors, and other factors). Furthermore, a criticality assessment was conducted to rank the factors based on their anticipated influence on PPE non-compliance. Finally, separate strategies to reduce the undesirable effects of each factor were provided. The identified factors, the criticality assessment, and the suggested strategies must be realized and purposefully implemented by upper management and safety personnel to reduce PPE non-compliance in construction workplaces. Accordingly, this study contributes significantly to the knowledge surrounding construction practices.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jsr.2023.02.008.

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Safety training in context: technical, cultural and political factors affecting its design, delivery and transfer

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ABSTRACT

Introduction: Safety training is integral to modern safety management systems. However, what is trained in the classroom is not always adopted and applied in the workplace, creating the training transfer problem. Taking an alternative ontological stance, the aims of this study were to conceptualize this problem as one of 'fit' between what is trained and the contextual factors in the work environment of the adopting organization. *Method*: Twelve semi-structured interviews were conducted with experienced health and safety trainers having diverse backgrounds and experience. Data were thematically coded 'bottom-up' to capture reasons for safety training and where consideration of context occurs in the design and delivery of training. Then, the codes were thematically grouped against a pre-existing framework to categorize contextual factors that affect 'fit' into technical, cultural, and political factors each operating at different levels of analysis. *Results*: Safety training occurs to satisfy external stakeholder expectations and meet internal perceptions of need. Consideration of contextual factors can occur both in the design and delivery of training. A range of technical, cultural, and political factors were identified, which can operate at individual, organizational, or supra-organizational levels to influence safety training transfer. *Conclusions*: The study draws particular attention to the influence of political factors and the impact of supra-organizational factors on the successful transfer of training, areas not consistently considered in safety training design and delivery. *Practical Application*: The application of the framework adopted in this study provides a useful tool for discriminating between different contextual factors and the level at which they operate. This could enable more effective management of these factors to improve the potential for transfer of safety training from the classroom to the workplace.

1. Introduction

Safety training is an integral and important part of modern safety management systems (Casey, Turner, Hu, & Bancroft, 2021) and aims to render staff competent to work effectively and safely. A recent meta-analysis of workplace safety interventions has shown that safety training improves both safety compliance and safety participation (Hutchinson, Luria, Pindek, & Spector, 2022). Crucially, the success of classroom-based training depends on the application of the lessons learned in the workplace (Ford, Bhatia, & Yelon, 2019). This is captured in the concept of transfer, which Ford and Weissbein (1997) define "as the extent to which knowledge and skills acquired in a training setting are generalized and maintained over a period of time in the job setting," p.34. However, while success depends on the effective application of what is learned in the workplace (Ford et al., 2019), this is not always achieved for a variety of reasons, creating the commonly reported 'training transfer' problem (Baldwin & Ford, 1988; Burke & Hutchins, 2007).

Transfer of safety training is acknowledged to be often problematic (e.g., Namian, Albert, Zuluaga, & Behm, 2016; Albert & Routh, 2021). According to a recent review by Chen, Ping, Zhang, and Yi (2022) who used a bibliometric method to map three related, but increasingly specific, groups of literature (namely training transfer, safety training and safety training transfer), there is a relatively small number of studies (n = 44) that have investigated safety training transfer. Nevertheless, these studies show that safety training transfer is affected by three high-level groups of factors: characteristics of the trainees (e.g., motivations, self-efficacy and ability); safety training design, specifically content and methods; and working environment, in particular opportunities to apply the training, the organizational climate and social support. Aligned

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with the earlier work by Hofmann, Burke, and Zohar (2017), Chen et al. (2022) indicated that urgent attention is warranted to identify those factors and their interrelationships that affect safety training transfer, suggesting that safety training transfer remains an important topic for further investigation.

Safety training differs from conventional training, with these differences creating unique challenges that hamper the successful transfer of safety training. Casey et al. (2021) drew attention to four such differences. First, safety training is often mandated, which can diminish individual choice, self-determinism, and engagement. Second, when safety behaviors become a normative obligation and regulated, workers might resist safety training programs. Third, often safety training programs are seen as redundant or irrelevant, reducing motivation. Training having only a compliance focus is especially vulnerable to this challenge as it becomes neither meaningful nor memorable (Dvorak, 2021). Finally, some safety training may only be practiced in an emergency, leading to a decay in expertise due to a lack of practice.

In an earlier review of training transfer, Ford and Weissbein (1997) noted that transfer effects can be examined at levels beyond the individual, suggesting that training transfer is a multi-dimensional phenomenon with multi-level influences (Burke & Hutchins, 2007; Sitzmann & Weinhardt, 2018) in need of further conceptual development (Ford et al., 2019). Adopting a different ontological stance on training transfer from the dominant psychological orientation of much of the training transfer literature, an alternative conceptualization of training transfer may be found in the notion of 'fit.' This is defined as, "the degree to which the characteristics of a practice are consistent with the (perceived) needs, objectives and structure of an adopting organization" (Ansari, Fiss, & Zajac, 2010; p68). Where the characteristics of a trained practice, including its content, better 'fit' the workplace environment and the context in which it is subsequently applied, then the transfer of what is learned becomes more likely.

Baldwin, Ford, and Blume (2009) indicated that trainees needed to customize their training to fit their job situation, while Grossman and Salas (2011) observed that employees increasingly required mutable skills so that workers were capable of adapting to specific environments. More recently, in their dynamic model of training transfer, Blume, Ford, Surface, and Olenick (2019) indicated that contextual factors influence transfer, and that individuals must tailor their transfer of new skills to the particular characteristics of their work environment. Consequently, generalized off-the-shelf training products may be ineffective because they do not consider local contextual factors. Casey et al. (2021) observed that "many safety training programs are designed as a one-size-fits-all solution," p307, suggesting that the audience needs, and work environment characteristics often are not considered, which, in turn, impedes the adoption and effective implementation of trained safety practices.

Additionally, the role of trainers in the transfer of training from the classroom to the workplace is vital, significantly influencing the design and delivery of training interventions (Burke & Hutchins, 2007). Acknowledging this vital role, several studies (Freitas & Silva, 2017; Freitas et al., 2017; 2019) have addressed the influence of safety professionals employed by organizations, including training as part of their job role, on safety training transfer. However, classroom-based safety training may also be designed and delivered by others operating independently and providing training to a wider range of different organizations. Their experience appears to be unreported.

The aims of this study were therefore to draw on the experience of safety trainers, who have acted with both in-house/internal and independent/external training roles, to investigate safety training transfer from an alternative ontolological stance using the concept of 'fit' and identify and categorize coherently the breadth of contextual factors operating at different levels that influence it. Specifically, the study aimed to address three questions:

(i) What purpose does safety training in organizations serve?
(ii) Where in the design and delivery of classroom-based safety training is context considered?
(iii) What contextual factors operating at different levels affect the 'fit,' and therefore likely adoption, of a trained safety intervention or practice in organizations?

Based on the premise that to achieve 'fit,' safety training needs to take account of the variety of organizational contextual factors in both the design and delivery of the training, 12 experienced health and safety trainers were interviewed. Following a review of relevant theories and studies in the following subsections, details of the methods and the findings from these interviews are presented, respectively, in sections 2 and 3 of the paper. Important contextual factors operating at different organizational levels that have important practical implications are considered in the discussion (section 4). The conclusions in section 5 draw attention to the influences both of contextual factors beyond the organization and the political nature of organizations on safety training transfer.

1.1. Training transfer and safety training

The success of classroom-based training depends on the effective transfer of learning from the classroom to the workplace (Cheng & Hampson, 2008), for "... much of what is trained fails to be applied in the work setting" (Ford & Weissbein, 1997, p22). This requires the transfer of training from one situation to another, which Salas and Cannon-Bowers (2001, p.488) conceptualize as the "... extent to which knowledge, skills and attributes (KSAs) acquired in a training program are applied, generalized, and maintained over some time in the job environment," echoing Ford and Weissbein (1997) earlier definition.

Generalization and maintenance are vital aspects of the conditions of transfer indicated in Baldwin and Ford (1988) original model of training transfer. Generalization considers the extent to which knowledge and skills are not simply learned but positively applied to settings, people, or situations different from those trained (Ford & Weissbein, 1997). This requires learners to tailor, or adapt, what they have learned to respond to variations in the context in which the learning is to be applied (Blume et al., 2019). Maintenance relates to preventing the degradation of skills and refers to the extent to which the changes arising from the training persist over time (Blume, Ford, Baldwin, & Huang, 2010), which is clearly contingent upon adoption. As both aspects of the conditions of transfer are influenced by context, Barnett and Ceci (2002) concluded that training transfer is highly contextualized. Although Baldwin and Ford (1988) indicated that the impact of context on training transfer could be examined empirically from a levels-of-analysis perspective, there appears to have been little or no response to this suggestion.

Over time, several literature reviews have identified factors influencing the transfer of training (e.g., Ford & Weissbein, 1997; Burke & Hutchins, 2007; Grossman & Salas, 2011). These studies mainly emphasize the importance of trainee characteristics, training design, and work environment as key groups of factors that affect the transfer process. Within these broad areas there are several notable themes. Trainee characteristics include their cognitive abilities and motivation, and perceptions of utility (e.g., is the training worthwhile?). In some studies (e.g., Burke & Hutchins, 2007; Grossman & Salas, 2011; Taylor, Russ-Eft, & Chan, 2005), training design includes role modeling behaviors and error management, whereas Baldwin and Ford (1988) refer to principles of learning and training content. Work environment includes the support available for transfer and the opportunity to perform the new task. Baldwin and Ford (1988) state that empirical evidence for the factors in the work environment affecting training transfer is sparse, a point reinforced by Brown and McCracken (2009). Lancaster, Di Milia, and Cameron (2013) concluded that of the three groups of factors affecting training transfer, the work environment had received the least attention. These three key groups of factors also pertain to safety training transfer as demonstrated in the review by Chen et al. (2022), although the supporting empirical evidence for the influence of work environment on transfer of safety training was sparse and mainly limited to the transfer climate, principally support by various others, and the safety climate more specifically.

An integrated model of the factors that influence safety training transfer was developed by Casey et al. (2021) based on a review of 38 articles from the safety training literature published between 2010 and 2020. This identified safety training engagement as a key, previously underexplored concept in learning and subsequent safety training transfer. Transfer of safety training was influenced by safety training design factors, safety training delivery factors and pre-training factors, and different facets of context were indicated to influence each of them. The model of Casey et al. (2021) also indicated that safety training transfer was affected by the opportunity to apply what was learned. Although context was indicated to influence the opportunity to apply, this was not the focus of the model, leaving this post-training relationship between different levels of context and application relatively underspecified.

1.2. Training transfer and the concept of 'fit'

The transfer of training involves the application of knowledge and skills acquired in a training program in the workplace (Salas & Cannon-Bowers, 2001). Often this knowledge and these skills are embedded in tools, techniques, and practices. These may or may not be immediately applicable in the workplace, and consequently may require adaptation to fit a specific work context (Blume et al., 2019). Identifying the contextual factors in the work environment operating at different levels of analysis that affect the opportunity to apply tools, techniques, and practice in the workplace is vital for successful training transfer. A primary aim of many safety training programs is the improvement of safety performance through the education of employees in the use of new tools, techniques, and practices and their subsequent adoption throughout the organization. According to Damanpour (2014) "the main challenge associated with [such] management innovations is in their successful adaptation and assimilation," p1271. This is a manifestation of the problem with training transfer, but from a sociological perspective rather than the psychological one that underpins much of the discussion of training transfer.

The concept of 'fit' defined above as "the degree to which the characteristics of a practice are consistent with the (perceived) needs, objectives, and structure of an adopting organization" (Ansari et al., 2010; p68), captures Damanpour's 'main challenge.' Where trained tools, techniques, and practices can be adapted to meet local needs (if they do not already do so), interventions are more likely to be assimilated, adopted, and applied. Where this is more difficult or unachievable, the trained interventions are less likely to be adopted and the knowledge and skills inherent in these interventions will not be transferred. Ansari et al. (2010) report that this concept of 'fit' is rarely considered, but is likely to be influenced by technical, cultural, and political factors in the work environment, and that these differ by level of analysis.

Incompatibilities between the trained practice and the context represented by technical, cultural, and political factors (Oliver, 1992) can affect adoption and may occur at individual/intra-organizational, organizational and supra-organizational levels (Ansari et al., 2010). Technical fit describes the extent to which characteristics of the trained practice or intervention are consistent with the technologies available in the new situation. At the intra-organizational level, this includes the technical background and experience of the employees, while organizational innovativeness and industry standards illustrate potential sources of incompatibility at organizational and supra-organizational levels, respectively.

Moreover, the beliefs, values, and working preferences of employees affect the transfer process as does the organizational culture and normative sector level discourses (Ansari et al., 2010; Gray, Purdy, & Ansari, 2015). Respectively, these illustrate cultural sources of potential incompatibility between the original practice and the new setting at the three different levels mentioned above. Finally, trained interventions embody a set of normative characteristics that may or may not be compatible with the local interests and agendas of adopters. This corresponds to the political fit (Ansari et al., 2010). Interests of individuals and groups within organizations may serve either to support or block the acceptance of new or revised practices arising from training initiatives (Damanpour, 2014). Similarly, factors such as government regulations or union agreements can influence adaptation and adoption at the supra-organizational level (Wijen, 2014).

Some of the technical, cultural, and political factors that generally influence 'fit' have been shown to affect the adoption of new knowledge and skills following safety training. For example, Demirkesen and Arditi (2015) demonstrated that safety training transfer is more likely in older, larger construction companies. Westrum (2004) showed the influence of organizational culture on the prioritization and management of safety, and therefore, the likelihood of successfully and effectively transferring learning and deploying trained safety interventions. Vignoli, Mariani, Guglielmi, and Violante (2018) investigated the influence of self-efficacy and leadership on the transfer of technical and non-technical skills for safety. Differences in perceptions of safety between different groups within organizations have been shown in the nuclear industry by Rollenhagen, Westerlund, and Näswall (2013) and by Gao, Bruce, and Rajendran (2015) in aviation, creating different responses to new safety interventions.

2. Methods

2.1. Participants

Consistent with a realist ontology the authors sought to access the 'reality' of safety training and the associated challenges of training transfer through conversations with experienced informants. 'Experience' is defined here as having more than 10 years practical experience of working in or for organizations, in at least two difference sectors, including international experience, to design and deliver safety training in the classroom to participants, ranging from front-line workers to board members, for both non-qualification and qualification purposes, and the latter to different levels.

Based on a convenience sampling strategy from the network of contacts available to the authors, 12 individuals agreed to participate in this study. Some of their demographic details are provided in Table 1. The sample included an academic from a university different to the authors' affiliation, a chief medical officer, two independent Health and Safety (H&S) training consultants, three directors of H&S training and advisory companies, three senior figures in internationally recognized providers of H&S training, and two senior staff from industry bodies supporting process safety.

Participants were based and worked in the UK, United States, Australia, the Netherlands, and Malaysia. There were five female and seven male participants. They had training expertise in both

Table 1
Demographic details and experience of the trainers interviewed.

Respondent Number	*Sex*	*Nationality*	*Experience (yrs)*	*Role when interviewed*
I1	Female	American	>10	Senior director workplace H&S training – international professional body
I2	Female	American	33	Senior H&S consultant and trainer – international professional body
I3	Male	British	26	Consultant – formerly H&S Director
I4	Male	Dutch	20	Consultant / Academic
I5	Female	British	>20	Director – Independent training company specializing in H&S
I6	Male	British	18	Head H&S Training design and development – international professional body
I7	Male	British	14	Academic
I8	Male	British	22	Chief Medical Officer
I9	Male	British	>15	Director – Independent H&S Training company – design and delivery behavior-based H&S training
I10	Female	Australian	>15	Director and H&S training designer – Industry body
I11	Male	German	>10	Global QHSE Manager – Global independent safety advisory company
I12	Female	Hungarian	>20	H&S Training director and designer – Industry body

process and occupational safety. Collectively, the interviewees had experience mostly in the private sector across a wide range of industries, including construction, oil and gas, nuclear, manufacturing, pharmaceuticals, health care, transport, telecommunications and entertainment. They had been delivering training at different qualification levels, ranging from vocational/undergraduate certificates through to master's degrees. The participants had also extensive experience in delivering continuing professional development courses to both front-line employees and senior management of organizations in both open program and in-company formats. All had considerable experience of observing the deployment of safety interventions in a range of organizations.

Through interviews, the authors sought to clarify the contextual parameters related to the design and delivery of classroom-based safety training and determine those factors operating at different levels of analysis that influence the subsequent adoption of the training in practice. Using experienced key-informants makes it more likely that consensus on important themes will be achieved more quickly, while simultaneously surfacing the breadth of important issues (Guest, Bunce, & Johnson, 2006). Those authors concluded that 'saturation' had occurred within the first 12 interviews from a sample of 60 interviews. Chionis, Karanikas, Iordan, and Svensson-Dianellou (2022) reached saturation after interviewing only 10 experienced safety investigators in their study of risk perceptions and communication in the aviation industry.

2.2. Data collection

An interview protocol (Appendix A) was shared with the interviewees in advance to allow them preparation time, secure considered responses, and strengthen data reliability and comparability. Following the collection of demographics (Question 1), the participants were asked about the consideration of context in the training they deliver (Question 2). Questions 3 and 4 were conditional to the responses to Question 2 and regarded how context is considered in training or why it is not considered, respectively. Question 5 aimed at collecting the overall experiences of the interviewees about the extent to which H&S training considers context, and Question 6 was about the perceived effects on organizational performance should context was considered in safety training programs. Last, the participants were prompted to list contextual factors (Question 7) and then specific organizational factors they believed could affect safety intervention effectiveness (Question 8).

The interviews were conducted online during August 2021 via Zoom by a single researcher to avoid interviewer variability in data collection. Eleven interviews lasted between 41 and 59 minutes, and one extended to 1.5 hours, accumulating to almost 10 hours of conversations. The interviews were audio recorded using the facility in Zoom. Transcription of these files was outsourced to a transcription service. Intelligent verbatim transcripts of each interview were cross-checked with the audio-recording and proofread by the first author to correct punctuation and misspelled or missing words as recommended by McMullin (2021).

2.3. Data analysis and reporting

All the transcripts were read by the lead author twice before coding commenced to get an overall sense of the available data. These qualitative data were analyzed using a form of thematic analysis, which is a widely adopted "method for identifying, analyzing and reporting [themes] within data" (Braun & Clarke, 2006; p.79). Initially, each transcript was free coded using the language of the informants into first order codes. The resulting first order codes from each of the 12 interviews were then collated.

Two alternative approaches to the subsequent coding of these free codes and analysis of the qualitative data were then deployed. First, following a form of template analysis outlined by Gioia, Corley, and Hamilton (2012), other first order codes from the 12 interviews relating to the purpose of safety training and where context was considered in the design and delivery of training were then combined through axial coding into second order themes that were labeled using more generic terms. These second order themes were then merged into two higher level aggregate dimensions.

Second, based on a reading of Ansari et al. (2010), first order codes that identified contextual factors that influenced the adoption of a practice in an organization post-training were categorized as technical, cultural, or political, and then were further differentiated depending on the level of their effect: individual/intra-organi zational, organizational and supra-organizational. This allowed the authors to create a 3x3 matrix of different types of contextual factors operating at different levels of analysis that influence the transfer of safety training.

Following an approach for the analysis of qualitative data reported by others (e.g., Zott & Huy, 2007; Jimmieson, Bergin, Bodia, & Tucker, 2021) the coding and grouping into themes was conducted by the first author. The second author then checked the text-code and code-theme correspondences provided by the first author. Any disagreements were resolved by referring to the data collected, and the codes generated.

As, to the best of authors' knowledge, this is the first study to investigate the contextual factors that influence the 'fit' between safety training and subsequent practice, the authors did not aim to present the magnitude or prevalence of the findings. Instead, the goal is to qualitatively offer a first, but representative, understanding of the landscape as an avenue to raise awareness of the

Table 2
Coding structure for data analysis.

1st Order Codes	2nd Order Themes	Aggregate Dimensions
General compliance Improvement notices Audit results Social pressure	Meet external expectations	Aim of training / Driver for training
Acquisition of skills H&S data Sense of unease Bottom-up innovation	Internal perception of need	
Approval process Customize / Standardize	Design process	Incorporation of context in training
Case study In-Class discussion E-learning	Delivery modes	
Competence of employees Individual attributes	Intra-organizational	Technical characteristics
Existing processes Size of organization	Organizational	
Regulatory context External standards Sector business models Societal challenge	Supra-organizational	
Management support Reporting lines	Intra-organizational	Cultural characteristics
Organizational culture Voice	Organizational	
National / societal culture	Supra-organizational	
Leadership beliefs / values	Intra-organizational	Political characteristics
Group-sub-group dynamics Employee relations Competing priorities	Organizational	
Unionization Legal context Sector level sharing State orientation towards H&S	Supra-organizational	

industry and stimulate broader studies, possibly including quantification.

3. Findings

The coding and theme structures that emerged from the data are presented in Table 2. The findings discussed in this section synthesize the responses from different individuals in correspondence with the respondent number (Table 1) and supported with verbatim quotes.

3.1. Why training?

The analysis suggests that there are two responses to this vital question (Table 3). First, training is implemented to meet the expectations of an external stakeholder. Where changes to legislation or regulations are introduced, then changes in practices may follow that necessitate training in the new practice. In contrast to these general requirements that affect all businesses, specific requirements may be placed on an organization following an audit or an inspection that may have arisen following an incident. Changes to current practices may require training. However, it was noted that in some cases training was an end in itself: "*It can be the case that training is just a way to say, 'Oh, we have done everything we can'* (I4)." It simply demonstrated to a third party that an organization had responded to a particular issue.

Second, training is implemented to meet internal perceptions of need. These may arise either from an inspection of health and safety data, which indicate that improvements are needed, or from a sense of unease that something needs to be done. These may be driven top-down in the organization and can often be implemented hastily or without sufficient consideration of the possible consequences. In one example given by an interviewee, the CEO of a company issued an edict that all platforms for working at height should be fitted with protection cages following a crush injury to a worker using this equipment. The unavailability of these cages in the African countries where this company operated meant

Table 3
Illustrative quotations of first order codes evidencing the different aims or purposes of safety training.

Illustrative quotes	1st Order Codes	2nd Order Themes
"It's what are you legally required to do, to maintain your license to practice as a business" (I8)	General compliance	Meet external expectations
"an intervention driven off the back of the regulatory intervention, an organization that's either had an accident or its been prosecuted, or it's been served an improvement or a prohibition notice" (I3)	Improvement notices	
"And [Organization] had a safety culture audit done a couple of years ago, and it was really bad. It looked like things were terrible. So I think [person] was under a lot of pressure from the manager to get something out there as quickly as possible (I7)".	Audit results	
Imagine you're in an organization that has a lot of sickness absence. A lot of it is around stress. Does putting mental health first aid in place help you with the problem? No, it doesn't. But it seems like an easy thing to do in order to look like you're doing the right thing (I5) *"But then improvement in the image, the brand value on reputation, everyone saying you can see we are committed, you can see the health and safety policy (I11)"*	Social pressure	
"there is a direct correlation between what they want to achieve [i.e. well-being of staff], the training that's delivered, and then the follow-up to show whether actually that was taking place or not" (I5) *"[The client] will say, why should I? What's the return on investment? So, you need data. This very much drives what we do to be able to say, if you have an early intervention programme . . ..you will get people back 35 days earlier" (I8).*	H&S data	Internal perception of need
"*an organization feels insecure, it doesn't have the knowledge, it doesn't know where to start* (I7)" "*They ended up doing safety management system assessments with us because they asked for training, but that really wasn't their issue, but to the untrained eye and to someone who is not really in safety, they might be in a leadership position, they feel like training is the go-to (I2)*"	Sense of unease	
"the training is to make people able to improve their work and safety and health at work, so they have to change their habits, or they have to maybe initiate improvements in the workplace (I4)"	Acquisition of skills	
"more often than not is that interventions are designed from the top-down and not from the bottom-up, and we need to get better at designing interventions with involvement from the people at the lower levels, because we'll end up with much better sustainable interventions (I3)"	Bottom-up innovation	

Table 4
Illustrative quotations of first order codes evidencing where considerations of context occur in safety training.

Illustrative quotes	1st Order Codes	2nd Order Themes
"So, when we develop a product, first thing we do is we talk to employers because they are really the kind of the end user in lots of way, they are the people who reap the benefits otherwise. So, we always talk to employer groups (I6)" *"we brought in 12 very senior health and safety practitioners from their organizations and said, sense-check this syllabus. You go through it line by line (I6)"*	Approval process	Design process
"We do empower people to bespoke the learning to their audience and that's what sets a good course apart (I6)" *"from the context in a private course, that really does – like the course is built around the organizational context and cultural norms, and, you know, I really make sure that I try and address what their symbols of leadership are (I10)"*	Customize / Standardize	
"you have to make decisions because you have the role, you have the role as an operator or supervisor or emergency manager depending on the theme of the case study, and then you discuss with your colleagues. It's a team exercise (I12)"	Case study	Delivery modes
"as you start a course or a class and people introduce themselves, you get a feel for who they are and where they are, and then they also talk about what they were hoping to get out of coming to us for this particular course, and the ability sometimes to take a little detour, one way or the other, in order to meet somebody's learning goal (I2)"	In-Class discussion	
"You can also use e-learning as a very standardized way of giving knowledge in a cheap way (I4)"	E-learning	

Table 5
Illustrative quotations of first order codes evidencing technical factors that influence 'fit' at different levels.

Illustrative quotes	1st Order Codes	2nd Order Themes
we need to stop just looking at people's technical abilities as well and start looking at their other skill sets that they've got when we're promoting people into certain positions at work (I6) *Generally, the most important is employees' competence level. You know, occupational health and safety training, you can't just throw it into your company and say, okay, fine, because competence level between, let's say, a manager and supervisor and, let's say, for floor staff are totally different (I11)*	Competence of employees	Intra-organizational
Demographic. Male/female, educated/uneducated (I5) *It is around people being decisive when they need to be, but also realizing when they need to listen, and having that level of self-awareness. And so, when you see people realize that actually self-awareness is going to help them through this if it happens to them, that can be really quite useful. (I10)*	Individual attributes	
I think another one of the issues that we have in terms of our interventions, they tend to be separate processes, as opposed to maybe trying to integrate your intervention with existing processes in a business (I3)	Existing processes	Organizational
I think with smaller organizations, they sort of pick and choose, and borrow and get and '-ize' it to their organization as far as [the] words around things that are specific to [their] industry, but maybe not necessarily around specific needs or competence or outcomes, at least (I2)	Size of organization	
Also, what's the regulatory territory that you're in, as well, because obviously, with any intervention that you do, you will have to keep an eye on what your country regulatory is saying about in terms of guidance, laws or codes of practice. Also, in fact, actually industry standards as well (I3)	Regulatory context	Supra-organizational
If you're thinking about doing an intervention, are there any industry standards that are relevant to this that I need to be aware of (I3)	External standards	
then there's the third bit, which is the discretionary spend, what's nice to have. And dependent upon whether its public sector/private sector or anything, their outlook on what that is, is completely different (I8)	Sector business models	
In the low middle-income countries, the driver is not so much the risk-based health and safety approach, it is public health. How do we keep out employees alive, so that they can actually come to work (I8)	Societal challenge	

that all work using these machines was halted there, even in situations where crush injuries were impossible. In this example, the situation was resolved subsequently by the introduction of changes to risk assessments. Alternatively, changes to practice were considered to be more effective when initiated bottom-up, because there was ownership of these changes, and the subsequent training was relevant.

3.2. Where is consideration of context given in safety training?

The interviewees noted that training can be used to provide knowledge and skills, which may not require consideration of context, or to support implementation, application or organizational change, which does require a consideration of context. Training may be used simply as a vehicle to communicate and deliver information that needs to be remembered rather than to provide skills required to interpret the information in different settings.

The analysis suggests that interviewees were unanimous in their view that consideration of context was important in safety training and would make a difference to safety outcomes. It also showed that context is considered at two points in the delivery of training (Table 4). The first point is at the design stage. Training courses can be standardized products, which contain little or no consideration of context. Standardization allows effective quality control and ensures a known content. The selection and choice of training is occasionally made by those with little or no knowledge of the products purchased or the setting in which they will be applied. Moreover, they are often seeking the cheapest rather than the most effective option.

> "It's one size fits all because of budget constraints or whatever, that's the way it's delivered (I1)".

Table 6
Illustrative quotations of first order codes evidencing cultural factors that influence 'fit' at different levels.

Illustrative quotes	1st Order Codes	2nd Order Themes
the resistance comes a bit further down, once you start hitting those middle managers who are less convinced about the need for the intervention or whether it's going to work (I3) *I remember also a case where people said, well, the most important danger in my job is my boss. So, then you have to do something about the boss, or you have to start communicating with the boss and it is also important that the people and the boss develop a new kind of conversation among them. It may take quite some time before it happens So, yeah, that is also context (I4)*	Management support	Intra-organizational
So, if we're training someone on a particular safety topic and that safety function within that organization reports to a vice-president or to the CEO, you're probably going to have a better chance of that being implemented than if that safety person is a lower-level person or perhaps reports into HR or into finance, for example (I1)	Reporting lines	
It sounds lazy, but obviously culture is the golden bullet (I6) *Understanding that the environment in which someone is working will determine what action they are likely to take in any given scenario . . . whether it is the cultural environment that they're in, in how they're encouraged, supported, do they have that level of psychological safety to be able to speak up (I10)*	Organizational culture	Organizational
It's all very lovely to say, you know, you have the power to stop the plant. And I get a lot of people telling me that in the training courses, I say okay that's great, when was the last time someone did it? Well, they have never done it. Well, why do you think they have the power to do it then if they've never done it? (I10)	Voice	
what is fundamental is actually to understand the country and their culture and religious behaviours (I11)	National / societal culture	Supra-organizational

Table 7
Illustrative quotations of first order codes evidencing political factors that influence 'fit' at different levels.

Illustrative quotes	1st Order Codes	2nd Order Themes
I would get a sense of where the leadership are in terms of attitudes and behaviors towards safety (I3) *There are so many other factors that have to be considered, such as what's the leadership's stance on [safety interventions] (I1)* *there are some things that will influence whether it's likely to be more or less effective, for example, you might have a top – a senior leadership team that is supportive or you might have a senior leadership that isn't supportive (I12)* *Having a leadership team who will listen, not accepting those unsafe behaviours, but also understanding why these unsafe behaviours take place (I6)*	Leadership beliefs / values	Intra-organizational
So how you can build capability in that particular site, which is in line with the corporate culture, the corporate view and vision and it may be the other way around as well because maybe the corporate is doing really, really like not so well or their safety culture doesn't show really big commitment towards safety, but they have really brilliant sites. And then it's the opposite. (I12) *the social interactions in the group that can also be important. Sometimes there is a strong subculture in a group. It is difficult to influence by leaders even (I4)*	Group-sub-group dynamics	Organizational
of course, ultimately, it's about what's the relationship then with the employees, the organizational relationship with the employees. That's quite the key as well. (I3)	Employee relations	
there are competing priorities at the supervisory level in particular, that's where it becomes a lynchpin and a stopping point. So, understanding what else the organization is trying to do simultaneously (I1)	Competing priorities	
The Trade Unions are in context are very important influencer. And you ignore them at your peril. (I8)	Unionization	Supra-organizational
First of all, it needs to be understood what are the differences between developing and developed countries in their legal system, in occupational health and safety, environment (I11)	Legal context	
I recently had nuclear experts attending a course because they wanted to apply some learning from process safety into nuclear safety. So that is one aspect that sectors are breaking down those wall and they are not working anymore in silos (I12)	Sector level sharing	
Then you come to the developed countries. Two ways to split them up is what I call the UK-US approach and the European approach. It is the punitive bullish approach and the caring nanny-state approach (I8)	State orientation towards H&S	

Conversely, rather than delivering generic materials, because "*H&S training without context is pointless (I12)*," the interviewees acknowledged that the needs of the client organization are better met by adapting or modifying existing training materials or creating new content. This involves a consideration of context.

> "So, your aspect of context is really fundamental in that. And the mistake to go to a client is to say, we think you should have this (I8)".

Developing training materials in collaboration with employees in the organization ensures that feedback is immediate and continuous, so that improvements can be made quickly. The approval process surrounding the development of a course or program can also have a profound influence on the content and delivery of materials. The interviewees noted that, in some cases, courses may be designed only by learning and development professionals without the involvement of H&S professionals. In other settings, courses may or may not have industrialists approving the content to evaluate the relevance of the materials to the practitioners participating in the course.

The second point is at the delivery stage. In the classroom, trainers draw on the experience of delegates or their own examples. This is prevalent in open programs with delegates coming from different organizations and where there is "*lots of context on the fly (I2).*" Similarly, discussion of 'war stories' (i.e., sharing of lived experiences in organizations) may also occur during the delivery of in-company programs too; in some cases, this may be an integral part of the design. These discussions allow questioning, which promotes understanding for the learner. Incomplete understanding reduces the chance of application subsequently and provided the basis for a critique of on-line learning. The "*complaint about online training . . . there is no place for someone to ask a question. There's no doubling back to see if that person can actually apply the skill set (I1).*" eLearning is an alternative to classroom-based training. While it was identified "*as a very standardised way of giving knowledge in a cheap way* (I4)," it was noted that the standardization of the product prevented a consideration of how the materials might be applied in context:

> "They leave you with the feeling, 'Okay, so now what?' When I finish the training course how can I apply it in my daily work? (I12)".

Some trainers, particularly from professional bodies, were strong advocates for the use of case studies. These allowed delegates to be involved in the unfolding decision making that led to the outcome illustrated in the case study. "*The way we present the case studies are that you go through the story as it unfolds itself. It starts not from the accident; it starts way before the accident occurred. Then you go through the story, what happened and what further information you receive (I12).*" This allows for an exploration of the influence of context on application, and so the scope for transfer.

While context was considered at these two points, many of the interviewees felt that context was generally overlooked, or at best left implicit, rather than being made explicit. With a sense of exasperation, one of the trainers remarked "*One of the things that I find so frustrating is actually when people don't recognize the context that they are in, and that that has an impact on what's going on (I10),*" while another observed that "*We assume people think about context – but they don't (I7).*".

3.3. Important contextual factors influencing safety interventions

The analysis revealed that interviewees collectively identified many contextual factors that influence the implementation of a safety intervention following training and that need to be considered during the design and delivery of safety training. One respondent understood, "*that something isn't just 'this is what it is' and we go plunk it into an organization, and it just works beautifully every time and it works the same way every time. There are so many other factors that have to be considered (I1).*" These factors have been classified into technical, cultural, and political factors operating at different levels of analysis using the framework developed by Ansari et al. (2010).

3.3.1. Technical factors (Table 5)

At the intra-organizational level, employees, both front-line workers and managers, should be knowledgeable and skillful operatives, competent in their job roles, and capable of deploying the interventions. It was noted that capability referred not only to the ability to understand what was required, but also to be physically and emotionally capable of performing the task. A range of individual level factors were identified that enable or hinder the successful implementation of a safety intervention. Some of these were demographic factors (e.g., education level) and others included psycho-social factors such as morale and resentment. Motivation to engage with the new intervention and how this could be engendered was also important.

Organizational size can influence the successful adoption and implementation of a trained safety intervention. Often small scale, and simpler, interventions are deployed in small-medium enterprises, whereas the complexities associated with successfully deploying any safety intervention in a multi-national company, for example, hampers the chances of successful adoption. Differences between public and private sector organizations in their processes and procedures, particularly around the procurement of interventions to support safety, influence the subsequent adoption and implementation. Furthermore, safety interventions are often developed independently from, and without reference to, existing processes. Successful adoption and implementation of these practices post-training is diminished because these additional processes increase workload and need to be adapted to fit existing practices, rather than being integrated into them.

The regulatory context of the industry and the local industry standards often determine what is required and what is acceptable. For example, one interviewee noted differences in approaches to risk assessment between the United States and the UK. The pursuit of external standards, including ISO standards, can influence the successful adoption of safety interventions. Sector differences, especially in their business models, may also influence the applicability of trained interventions. Where profit margins are minimal, as in the construction sector, resource availability for safety may be less than in other sectors. Geographic differences may also prioritize some contextual considerations over others, which may influence training. In less developed countries, considerations of nutrition and disease status of the workforce may be primary, and considerations of mental health secondary.

3.3.2. Cultural factors (Table 6)

Managers need to be committed to the training and the implementation of what is learned. In large organizations with a sizable cadre of middle managers support for a safety intervention can be easily diluted, even if the senior management team is very supportive. Managers also need to be technically competent and able to understand the issues on the shop floor. The focus of their attention, and often that of the front-line workers, is often driven by what gets measured. This can influence the likely adoption of a particular trained safety practice. The reporting lines for these metrics influence the importance attached to it, and subsequent actions.

The interviewees unanimously identified organizational culture as one important contextual factor that determines whether a trained safety intervention will be deployed. Organizational culture, particularly the importance attached to safety, will determine whether organizations will pursue minimal compliance with regulations and standards, or seek best practice. Organizational culture will also influence whether employees are encouraged to speak up concerning safety issues without fear of adverse consequence, and this affects the likely adoption of practices. An acid test of the rhetoric around positive safety culture is whether anyone has ever stopped production and been supported in doing so.

National cultures also influence beliefs about health and safety, create attitudes toward safety practices, and subsequently, affect the adoption of safety interventions. Raising safety concerns in the workplace may be inconsistent with life experience beyond the workplace. For instance, restricting the work on flatbed lorries may be inappropriate where it is acceptable to ride to work on the roof of a bus.

3.3.3. Political factors (Table 7)

The beliefs and values expressed in behaviors and attitudes of senior managers and leaders toward safety was identified as a critical factor. They are integral to supporting and driving a safety intervention throughout the organization. Without their commitment and support, any intervention is likely to fail. This extends across the organization to anyone with leadership responsibilities, including supervisors. It is important that leaders are visible and engage with the workforce, listen to their concerns, and remain open to suggestions.

The analysis indicated that relationships between different groups within an organization, particularly where they are adversarial, can also influence the adoption and effectiveness of safety interventions post-training. Differences in intent or ambition are commonly seen between the headquarters of an organization and sites or subsidiaries geographically distant from the central office, leading to centrally determined activities not always being deployed as intended. Differences are also visible between groups within an organization, for example between professionals and managers. These tensions can affect adoption of a new practice. Different groups may display different cultures, with individuals working in these groups displaying different behaviors and attitudes. More generally, employee relations with management can affect adoption of new interventions or the adherence to existing practices. Better relationships are promoted by two-way, open communication that encourages the development of trust, which "*comes in on a tortoise and goes out on an antelope* (I6)." The presence or absence of a unionized workforce was also identified as a factor that influences the engagement with safety training and the likely implementation of trained safety interventions.

Several important enablers and barriers internal to the organization that affect effective safety interventions were also identified in the analysis. The availability of time and resources to support the development and deployment of interventions is a crucial factor. This is particularly important in large multi-site organizations where the cost of deploying a new intervention may be high, and where other, potentially conflicting, initiatives may also exist. The complexity of the intervention being deployed is also important because large complex interventions generally require more resources. Other immediate priorities within the business can influence the effective adoption of an intervention. Moreover, other organizational change initiatives running in parallel compete for resources, especially at the front-line, making it challenging to effectively deliver any of the initiatives. A downturn in the industry requiring a focus on performance output or the shedding of staff can distract from effectively deploying a safety initiative.

Local legal requirements can also determine what is required. Understanding these before attempting to make safety interventions will result in a more successful outcome. This can also create a moral dilemma for organizations that work internationally across different legislative regimes: Should an intervention be applied to all employees in the organization irrespective of the local legal requirements, or should the intervention only be locally compliant, thereby creating different standards across the organization? One of the interviewees illustrated this by reference to display screen equipment assessments. In some countries, like the UK, this is a requirement, and appropriate provision should be made; in others it is not.

Differences in state-level attitudes toward health and safety concerns may also influence the adoption of interventions and the way they are deployed. This was illustrated by reference to the differences between European countries in their implementation and response to drug and alcohol testing in the workplace. Some countries adopt a more punitive stance, while in others it is a supportive one. Sectors also differ in the extent to which information is shared between organizations, and lessons are learned. Aviation has a strong history of collaboration and sharing, which is not similarly present in other sectors.

4. Discussion

4.1. Factors affecting 'fit' between safety training and the workplace

Safety is an integral part of work practices and processes. An important aim of safety training is to ensure employees have the necessary knowledge and skills to carry out their required activities in a safe manner. This requires the transfer of what is learned in the classroom to the workplace, so that what is trained is adopted and assimilated into work routines. However, this often fails and creates the 'training transfer' problem. Ford et al. (2019) suggest that training transfer needs further conceptual development. A sociological orientation to this training transfer problem suggests that the concept of 'fit,' typically applied to the investigation of the successful (or otherwise) adoption of innovations in practices and procedures in new organizational settings, addresses the same phenomenon. Adopting this approach by using the framework proposed by Ansari et al. (2010), the authors have been able to address Baldwin and Ford (1988) concern by providing empirical evidence for a coherent set of factors operating at different levels in the work environment that influences safety training transfer. Moreover, by capturing this coherent set of factors in a single study, the authors address the imbalance noted in previous studies (Blume et al., 2010; Bell, Tannenbaum, Ford, Noe, & Kraiger, 2017) where several factors in the work environment have received considerable attention to the neglect of others.

In this study, experienced safety trainers reported that the influence of context is considered in both the design and delivery of training as suggested by both Casey et al. (2021) and Chen et al. (2022) in their recent reviews. Alignment of training content with workplace practices at the design stage is essential for success. Incorporating an approval process helps to ensure this. Consideration of context also occurred at the delivery stage. Some modes of delivery were more effective at incorporating contextual factors than others. Case studies and discussions lend themselves to considerations of the influence of contextual factors where standardized e-learning materials do not.

The framework of technical, cultural, and political factors that influence 'fit' operate at three different levels of analysis: individual, organizational, and supra-organizational. Investigation of factors influencing safety training transfer typically focus on individual characteristics, on support provided by others, and safety climate. Apparently, little attention has been given to the influence of factors operating beyond the organization. Casey et al. (2021) suggest that national culture differences may influence the effectiveness of safety training transfer through learner engagement, but this remains underexplored.

Individual characteristics influence the adoption of safety interventions. Although the former is recognized in several frameworks describing training transfer (Grossman & Salas, 2011; Sitzmann & Weinhardt, 2018), reports of safety training focus primarily on motivation, self-efficacy, and cognitive ability (Chen et al., 2022). A recent review of 73 empirical studies of the design and implementation of safety interventions (Karanikas et al., 2022) indicates that, while cognitive aspects, such as knowledge and skills, were frequently considered, physiological and emotional factors were astonishingly underrepresented. The interviewees drew attention to the common assumption that everyone can deploy any safety intervention if properly trained, but recognized that this is not always the case. Disabilities of different degrees may negate this presumption, as, for example, different degrees of intellectual disability affect the level of human functioning and the level and type of support required (Shogren, Luckasson, & Schalock, 2014).

At an organizational level, the interviewees indicated that 'fit' may be strongly influenced by the characteristics of the business, particularly sector and size. Adoption practices in public sector organizations, which are typically larger and more bureaucratic, will differ from private sectors organizations, many of which are small with only a few employees. Small and medium-sized enterprises (SMEs) dominate the economy of many countries, including the UK (Roland, 2020). Moreover, it is anecdotally acknowledged that SMEs are hard to reach in terms of safety training, and therefore the adoption of new practices is likely to be correspondingly low (Demirkesen & Arditi, 2015). It was also recognized by the interviewees that the pursuit of ISO standards can drive specific behaviors to the exclusion of others, which may not be consistent with improving safety performance (De Oliveira Matias & Coelho, 2002). Safety interventions that do not align with this ambition are less likely to be supported and adopted.

Leaders and managers or supervisors have a strong influence on the adoption of safety interventions by employees (e.g., Vecchio-Sadus & Griffiths, 2004) regardless of the training provided. While senior leadership can initiate, support, and encourage the adoption of particular safety interventions, the interviewees also acknowledged their effective application at the frontline is strongly influenced by the cadre of managers and supervisors organizing work on a daily basis and demonstrating their own safety behaviors (e.g., Clarke, 2013; Lingard, Cooke, & Blismas, 2012). Sinelnikov, Bixler, and Kolosh (2020) recently reviewed the role of work-unit supervisors on organizational safety and concluded that training to improve their safety knowledge, attitudes, and behaviors had a positive effect on occupational safety.

Where training is mandated, or perceived to be irrelevant or unnecessary, support to initiate post-training changes will be low (Casey et al., 2021). Similarly, where any intervention conflicts with other dominant priorities such as production (Pagell, Klassen, Johnston, Shevchenko, & Sharma, 2015), support will also be reduced regardless of whether safety training was offered to bring changes. Processes, for which operational rules are not aligned or conflict, are likely to inhibit adoption of trained interventions, as illustrated in the operations of a factory in the Netherlands (Mascini, 2005) and confirmed by the interviewees in this study.

The interviewees indicated that different groups of employees in the same organization can also respond differently to training in new safety interventions, both positively and negatively. In some instances, this may be manifest in differences between professional staff and managers, in other cases, there could be a difference between unionized and non-unionized workforce (Gillen, Baltz, Gassel, Kirsch, & Vaccaro, 2002; Demirkesen & Arditi, 2015). A further distinction between permanent and temporary employees has been made by Luria and Yagil (2010). They suggest that temporary employees are more concerned with self-interest than permanent employees who act in the interests of the group or organization. Such differences are likely to affect the adoption of safety interventions and comprise contextual factors that influence safety training transfer.

At the supra-organizational level, external environmental conditions can also influence the success of training in, and deployment of, new safety interventions. Global differences in national cultures were acknowledged to encourage or preclude the adoption of particular safety interventions (Reader, Noort, Shorrock, & Kirwan, 2015). For example, differences between cultures in the power distance between managers and employees can discourage reporting (Starren, Hornikx, & Luijters, 2013). Arabic cultural values that privilege family connections and social harmony militate against the development of 'just' and 'reporting' cultures (Ben-Saed & Pilbeam, 2022).

Applying this framework to our empirical investigation of training transfer has helped to more fully elucidate the set of contextual factors that set the boundaries of the theory (in this case of training transfer) and delimit its range, as advocated by Whetten (1989). Furthermore, the foregoing discussion suggests that it has provided a coherent organizing framework for the findings from existing studies too.

4.2. Practical considerations

The 3x3 matrix of technical, cultural, and political factors operating at individual/intra-organizational, organizational, and supra-organizational levels provides a framework that can be used to identify factors that adversely affect training transfer and simultaneously suggest where interventions that complement and support training could be targeted. The analysis of the data using this framework draws attention to several important practical considerations. From a technical perspective, not all employees are identical, and their training needs and levels of competence may differ substantially. Current standardized safety training overlooks these increasingly important demographic considerations, and how this may impact training transfer. Moreover, current interventions to improve organizational safety that are the subject of safety training are often developed independently from existing processes. This creates potentially conflicting processes and additional work. Health and safety professionals developing new interventions should work in partnership with other functions to integrate improvements into existing processes to render deployment post-training more successful.

Organizational culture and the level of support given to safety are contextual factors that significantly influence safety training transfer. Regular audits of safety climate using existing cross-industry scales (e.g., Beus, Payne, Arthur, & Munoz, 2019) or industry-specific scales (Casey, Hu, Kanse, & Varhammar, 2022) and subsequent targeted interventions to enhance safety climate may also simultaneously encourage safety training transfer. Importantly, the framework also draws attention to the political nature of organizations. Adversarial relationships in an organization, between different groups having different agendas, have a significant impact on safety training transfer. Ultimately, they may result in divergent safety practices and safety performance across groups or units within an organization. Different perceptions and understandings of safety can also arise from differences in geographic location. Such variation makes the standardization of safety practices problematic, especially in organizations operating in multiple locations, or with a diverse workforce drawn from different cultural backgrounds.

In their review of the effectiveness of safety training interventions, Sinelnikov et al. (2020) drew attention to the lack of understanding behind the decision-making processes regarding training. This was commented upon also by interviewees in this study, who raised two important practical questions for organizations to consider. First, is the training effective? An evaluation by organizations of the effectiveness of safety training they provide in-house or outsource appears to be uncommon and may not be high. Albert and Routh (2021) note that "training interventions do not [always] yield tangible benefits and may sometimes simply reduce to wasted resources." An inquiry into the extent of the benefits achieved through training is often absent. This failure to evaluate effectiveness may conceal a significant unnecessary cost to organizations given the considerable budgets spent on training annually (Sitzmann & Weinhardt, 2018). According to an early Health and Safety Executive report (HSE, 2003), per capita expenditure on compliance with UK H&S regulations, including training, is disproportionately greater for employees in SMEs that can perhaps least afford to waste money.

Second, is training needed? Is it the most appropriate safety intervention for the particular situation? Interviewees in this study identified a variety of different motivations for training driven either by requirements of external stakeholders, or by a perception of need from within the organization. While providing safety training is a relatively easy and simple response to a safety issue, and one that can be adopted quickly and demonstrably, not all safety issues can be resolved through training. Some safety challenges may not be competence related, but rather issues of design to be better tackled by actions at different levels of the hierarchy of controls. Training is an example of administrative controls, at the lower end of this hierarchy. Changes in design, occurring further up the hierarchy of controls, can isolate people from hazards (engineering controls), replace hazardous components or elements (substitution), or remove the risk (elimination), but require thorough and careful planning before implementation. This is likely to be complicated and take time and effort and necessitate organizational change, and, consequently, may be unpopular. Evaluating the choice of intervention implemented appears to be a vital requirement (Sinelnikov et al., 2020) if improvements in organizational safety are to be made.

4.3. Study limitations and future work

This study has several limitations. The data were collected from a limited number of respondents, albeit knowledgeable and very experienced trainers. Other trainers with different demographic characteristics and different levels of experience may identify different or additional factors that influence the training transfer process. Furthermore, the data presented come from the aggregation of factors identified from the interviews, during which each trainer considered different training interventions and their application to different contexts. This provides a generalized set of data, but provides no indication of the causality between the particular factors and the (un)successful transfer and subsequent adoption of a specific intervention. Finally, the focus of the interviews was on training interventions taught in classroom settings, meaning the transfer from classrooms to workplaces. Thus, this study did not account for factors that influence the transfer of online learning to the workplace, or 'workplace' learning or 'on-the-job' training (Cheng & Hampson, 2008), although the authors expect that many of the same factors influence transfer in these settings too.

Four avenues for further research present themselves from this study. First, and following the earlier noted limitation, the factors that influence the effectiveness of workplace learning to improve safety merit thorough investigation. A recent study showed that workplace learning can unwittingly promote unsafe work practices preventing necessary safety improvements (Grytnes, Nielsen, Jørgensen, & Dyreborg, 2021). The contextual factors that influence the effectiveness of this learning process may differ from those that affect the adoption of classroom-based training. Second, online training is relatively more standardized than classroom-based training. This may make the transfer of what is trained more vulnerable to a wider range of contextual factors. With the growth in this mode of delivery of safety training, further investigation of enabling and limiting factors for transfer of online training is warranted. Third, this study identified a small number of characteristics of successful trainers. These included experience of the industry and similar demographic characteristics to the participants, as well as training experience. Building on the work of Freitas and Silva (2017), the contribution trainers make to effective and successful training requires more extensive investigation to generate a more comprehensive set of essential characteristics or core competencies. Their role in the contextualization processes should also be investigated further. Finally, transfer is a dynamic process that unfolds over time (Blume et al., 2019) and warrants a systematic investigation of the evolution of 'fit' through the design, delivery, and on-going implementation of safety training interventions. This may contribute to a deeper understanding of 'far transfer' (Barnett & Ceci, 2002).

5. Conclusion

Training is a commonly deployed safety intervention. However, its purpose is often ambiguous, designed to satisfy external stakeholders or to meet internal needs, and surprisingly its effects are not commonly evaluated. Effective training depends on the successful transfer of what is learned in the classroom to the workplace. A process that is influenced by a variety of contextual factors. This study re-conceptualize training transfer using the notion of 'fit' from innovation adoption studies, allowing the authors to categorize influential contextual factors into technical, cultural, and political categories and to discriminate them according to their level of influence: individual/intra-organizational, organizational, and supra-organizational.

The substantial, if not fully comprehensive, set of contextual factors identified by 12 experienced safety trainers highlights, for the first time, the importance of supra-organizational factors on training transfer. The categorization also draws attention directly to the political nature of organizations and how this shapes what is and is not acceptable to different groups, and so whether adoption of trained practices in the workplace is likely. Greater awareness of these factors and their relationships to the design and delivery of safety training may improve the subsequent adoption of the taught practice or intervention, minimizing the training transfer problem, and more importantly, improving safety outcomes in the workplace.

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Appendix A. . Interview questions.

1. Please could you briefly describe your experience of delivering training in Occupational Safety and Health.
   - What topics do you mainly focus on?
   - What sectors / industries?
   - What level do you train?
   - Are there particular interventions / practices / methods you train?
2. In your training
   - Do you consider how context might influence the performance of these interventions?
   - Do you consider whether the interventions might need to be changed in some way to be effective?
3. ***IF YES (to Q2)***: Where it is considered, why does this occur?

- Is this consideration of 'contextualisation' included in the formal design (curriculum) of the training courses you offer? OR does it 'happen' (through discussion/conversation) informally during the training event?
- What contextual factors do you consider in the design of the training course? Or during the training event? Why these in particular?

4. ***IF NO (to Q2)***: Where it is not considered, please explain why you think this is the case?
   - Would it make a difference to the people you train if it were considered? Why?
5. As far as you are aware, to what extent does H&S training take account of contextual influences?
   - Why do you think this is the case?
   - Can you provide some examples of where it does and where it does not?
6. Based on your experience, do you think it would make a difference to organizational safety outcomes (such as OSH performance, safety behaviours) if contextualisation was considered in training on particular safety interventions? Why?
7. Based on your experience, what are the contextual factors someone should consider when designing and implementing a safety intervention? Why these?

8. Based on your experience, what are the most important aspects of organizational context that influence the effectiveness of safety interventions? Why? How?

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Workplace violence against health care workers during the COVID-19 Pandemic: A systematic review and meta-analysis

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A B S T R A C T

Introduction: During the COVID-19 pandemic, Health Care Workers (HCWs) have been at the frontline against the disease and have direct contact with patients and their companions, so they are exposed to all sorts of Workplace Violence (WPV). The aim of this study was to investigate the prevalence of WPV against HCWs during the COVID-19 pandemic. *Method:* This study was conducted according to the PRISMA guideline, and its protocol was registered at the PROSPERO under the code of CRD42021285558. Articles were obtained from data resources such as Scopus, PubMed, Web of Science, Science Direct, Google Scholar, and Embase. A literature search was conducted from the beginning of 2020 to the end of December 2021. Meta-analysis was conducted using the Random effects model, and the I^2 index was used to check the heterogeneity. *Results:* In this study, 1,054 articles were initially obtained during the primary search, of which 13 were finally entered in the meta-analysis. According to the results of the meta-analysis, the prevalence of physical and verbal WPV were 10.75% (95% CI: 8.20–13.30, I^2 = 97.8%, P = 0 < 001) and 45.87% (95% CI: 36.8–54.93, I^2 = 99.6%, P = 0 < 001), respectively. The overall prevalence of WPV was obtained, 45.80% (95% CI: 34.65–56.94, I^2 = 99.8%, P = 0 < 001) were reported. *Conclusion:* The results of the present study showed that the prevalence of WPV against HCWs was relatively high during the COVID-19 pandemic; nevertheless, it was lower compared to the area prior to the pandemic. Therefore, HCWs need essential training to reduce stress and increase resilience. Also, considering organizational interventions (including policies to ensure that HCWs report WPV to their supervisors, increasing staffing per patient, and installing systems for HCWs to call for immediate assistance) can increase the resilience HCWs.

1. Introduction

According to the definition by the World Health Organization (WHO), Workplace Violence (WPV) includes work-related threatening, insulting, and harassing of employees, which can also happen when commuting to and from the workplace, and poses evident challenges to their safety and well-being (Fute, Mengesha, Wakgari, & Tessema, 2015; ILO & WHO, 2003). WPV can encompass physical, verbal, and psychological forms (Tee, Özçetin, & Russell-Westhead, 2016) and can occur in any organization, against anyone, and at any time; however, health care workers (HCWs) more frequently experience this phenomenon (Abdellah & Salama, 2017; Anand, Grover, Kumar, Kumar, & Ingle, 2016). According to studies, more than half of HCWs are exposed to some sort of violence, including verbal violence, during their careers (Pinar et al., 2017).

Health care workers are in close contact with patients and their families during health care provision in care centers. On the other hand, patients and their companions, due to their medical situation, drug side effects, or dissatisfaction with the services provided, may exude aggressive and violent behaviors (Al-Turki, Afify, & AlAteeq, 2016). So, HCWs are exposed to WPV due to direct contact with patients (Sheikhbardsiri, Afshar, Baniasadi, & Farokhzadian), which can negatively impact their mental health, leading to absenteeism and compromising health system effectiveness (Sun et al., 2017). Also, WPV against HCWs can ensue several adverse consequences such as anger, anxiety, depression, fear, sleep disturbance,

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job dissatisfaction, and job withdrawal (Lin et al., 2015). The results of a review study in China showed that the prevalence of WPV against HCWs was 62.4%, and the rates of physical, verbal, and psychological violence were 13.7%, 61.2%, and 50.8%, respectively (Lu et al., 2020). The results of a study in the United States that examined workplace violence events reported the rate of physical, non-physical, and physical and non-physical violence as 27%, 27%, and 41%, respectively (Tiesman et al., 2022).

During the COVID-19 pandemic, HCWs fought at the forefront of the war against the disease, exposing themselves to risks such as long working hours, psychological distress, exhaustion, and burnout, as well as severe fear, labeling, and rejection, particularly when providing care to patients with Covid-19 (Rodríguez-Bolaños et al., 2020). Thus, HCWs experienced a variety of psychological consequences during the COVID 19 pandemic (Adibi et al., 2021; Jahangiri & Sahebi, 2020). According to studies, the most common causes of violence against HCWs during the COVID-19 pandemic include mistrust in HCWs, death of COVID-19 patients, hospitals' refusing to admit COVID-19 patients due to limited space, and hospitals' COVID-19 policies (Bhatti, Rauf, Aziz, Martins, & Khan, 2021). The authors found no comprehensive studies addressing the prevalence of WPV against HCWs during the COVID-19 pandemic, so we decided to conduct a systematic review and meta-analysis to investigate the prevalence of this phenomenon during the current pandemic. The results of this study can be beneficial for health managers as an information source for future planning.

2. Materials and methods

The Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) guideline was employed to conduct this systematic review and meta-analysis (Moher, Liberati, Tetzlaff, Altman, & Group, 2009). The protocol of this review was also registered at the International Prospective Register of Systematic Review (PROSPERO) database under the code of CRD42021285558.

3. Search strategy

In this study, a comprehensive search was conducted in valid data resources, including Scopus, PubMed, Web of Science, Science Direct, Google Scholar, and Embase to obtain related studies. Also, other sources such as key journals, conference proceedings, and the reference lists of selected studies were searched to identify relevant studies. Valid English keywords were used, including: "Workplace Violence,*" "Aggression,*" "Harassment,*" "Bullying," "Workplace Bullying," "assault,*" "Abuse," "Physical Abuse," "Violence," "Assaultive Behavior," "Health Care Provider,*" "Health Personnel," "Healthcare Provider,*" "Healthcare Worker,*" "Medical staff," "Medical Worker,*" "Health Care Professional,*" "COVID 19," "COVID 19 Virus Disease,*" "COVID-19 Virus Infection,*" "2019-nCoV Infection,*" "Coronavirus Disease-19," "2019 Novel Coronavirus Disease," "2019 Novel Coronavirus Infection," "2019-nCoV Disease,*" "COVID19," "Coronavirus Disease 2019," "SARS Coronavirus 2 Infection," "SARS-CoV-2 Infection," "SARS CoV 2 Infection,*" "COVID-19 Pandemic.*" In order to compile a search strategy using keywords and operators, a strategy was initially designed in the PubMed database, based on which search strategies in other databases were produced. The searches were conducted in both Persian and English from the beginning of 2020 to the end of December 2021. Search strategies in various databases have been noted in Table 1.

3.1. Inclusion criteria

In this review, the studies reporting the prevalence of various types of WPV against HCWs at work during the COVID-19 pandemic in English were included.

3.2. Exclusion criteria

Review studies, case reports, interventional studies, letters to editors, and studies on WPV against HCWs during periods other than the COVID-19 pandemic were excluded.

3.3. Selection of studies

Initially, all the studies identified in the primary literature search were entered into EndNote 7 software. After removing duplicates, the titles and abstracts of 931 studies were screened. Next, two researchers independently studied the full texts of 22 possibly related studies in detail, and finally, 13 studies were

Table 1
Search Strategy in Various Databases.

Data base	Search strategy
Pubmed	(("Workplace Violence*"[tiab] OR Aggression* OR "Harassment*" OR Bullying OR "Workplace Bullying" OR assault* OR Abuse OR "Physical Abuse" OR Violence OR "Assaultive Behavior") AND ("Health Care Provider*" OR "Health Personnel"OR "Healthcare Provider*" OR "Healthcare Worker*" OR "Medical staff" OR "Medical Worker*" OR "Health Care Professional*") AND (COVID 19 OR "COVID 19 Virus Disease*" OR "COVID-19 Virus Infection*" OR "2019-nCoV Infection*" OR "Coronavirus Disease-19" OR "2019 Novel Coronavirus Disease" OR "2019 Novel Coronavirus Infection" OR "2019-nCoV Disease*" OR COVID19 OR "Coronavirus Disease 2019" OR "SARS Coronavirus 2 Infection" OR "SARS-CoV-2 Infection" OR "SARS CoV 2 Infection*" OR "COVID-19 Pandemic*"))
Scopus	((TITLE - ABS ("Workplace Violence*") OR ALL(Aggression*) OR ALL("Harassment*") OR ALL(Bullying) OR ALL("Workplace Bullying") OR ALL(Assault*) OR ALL(Abuse) OR ALL("Physical Abuse") OR ALL (Violence) OR ALL("Assaultive Behavior")) AND (ALL("Health Care Provider*") OR ALL("Health Personnel") OR ALL("Healthcare Provider*") OR ALL("Healthcare Worker*") OR ALL("Medical staff") OR ALL("Medical Worker*") OR ALL("Health Care Professional*")) AND (ALL(COVID 19) OR ALL("COVID 19 Virus Disease*") OR ALL("COVID-19 Virus Infection*") OR ALL("2019-nCoV Infection*") OR ALL ("Coronavirus Disease-19") OR ALL("2019 Novel Coronavirus Disease") OR ALL("2019 Novel Coronavirus Infection") OR ALL("2019-nCoV Disease*") OR ALL(COVID19) OR ALL("Coronavirus Disease 2019") OR ALL("SARS Coronavirus 2 Infection") OR ALL("SARS-CoV-2 Infection") OR ALL("SARS CoV 2 Infection*") OR ALL("COVID-19 Pandemic*")))
Web Of Science	((TS= ("Workplace Violence*") OR TS=(Aggression*) OR TS= ("Harassment*") OR TS= (Bullying) OR TS= ("Workplace Bullying") OR TS= (Assault*) OR TS= (Abuse) OR TS= ("Physical Abuse") OR TS= (Violence) OR TS= ("Assaultive Behavior")) AND (TS= ("Health Care Provider*") OR TS= ("Health Personnel") OR TS= ("Healthcare Provider*") OR TS= ("Healthcare Worker*") OR TS= ("Medical staff") OR TS= ("Medical Worker*") OR TS= ("Health Care Professional*")) AND (TS= (COVID 19) OR TS= ("COVID 19 Virus Disease*") OR TS= ("COVID-19 Virus Infection*") OR TS= ("2019-nCoV Infection*") OR TS= ("Coronavirus Disease-19") OR TS= ("2019 Novel Coronavirus Disease") OR TS= ("2019 Novel Coronavirus Infection") OR TS= ("2019-nCoV Disease*") OR TS= (COVID19) OR TS= ("Coronavirus Disease 2019") OR TS= ("SARS Coronavirus 2 Infection") OR TS= ("SARS-CoV-2 Infection") OR TS= ("SARS CoV 2 Infection*") OR TS= ("COVID-19 Pandemic*")))

selected for quality assessment. Any disagreement in these steps was resolved by including a third researcher.

3.4. Quality assessment and data extraction

Two of the researchers independently used the Appraisal Tool for Cross-Sectional Studies (AXIS) tool (Downes, Brennan, Williams, & Dean, 2016) to evaluate the quality of the selected studies. The score obtained from this tool ranged between 0 and 20. A score higher than 12 was considered as good quality. Any disagreement between the researchers was resolved through group discussion with a third researcher. Data extraction from the final studies included in the study was independently performed by the two researchers using a pre-prepared checklist, documenting the first author's name, mean age of participants, place of study, sample size, number of males and females, and the prevalence of WPV and its variants. Any disagreement between the two researchers was resolved through discussion with a third investigator.

3.5. Statistical analysis

The simple random effects model was used for meta-analysis. The degree of heterogeneity among the studies was calculated using the I^2 index (indices below 25%, 25–50%, 50–75, and above 75% indicating no heterogeneity, moderate, high, and very high heterogeneity, respectively; Sahebi, Abdi, Moayedi, Torres, & Golitaleb, 2021). Publication bias was assessed utilizing the Egger test. Data were analyzed using STATA software (version 14).

4. Results

In this study, 1,054 articles were initially identified in the primary literature search, and after removing duplicates, 931 studies were screened. Of the studies screened, 22 studies were selected for full-text evaluation, and finally 13 studies were chosen for quality assessment; all of which finally entered the meta-analysis phase (Fig. 1). Based on the quality assessment results, the quality score of the included studies ranged from 14 to 18. In these studies, 31,779 HCWs had been screened in terms of experiencing WPV during the COVID-19 pandemic, of whom 4,987 were male, and 26,792 were female. All the studies selected had a cross-sectional design (Table 2). The results of meta-analysis showed that the rates of physical and verbal WPV were 10.75% (95% CI: 8.20–13.30, $I^2 = 97.8\%$, $P < 0.001$) (Fig. 2) and 45.87% (95% CI: 36.8–54.93, $I^2 = 99.6\%$, $P < 0.001$) (Fig. 3), respectively. The overall prevalence of WPV against HCWs was obtained as 45.80% (95% CI: 34.65–56.94, $I^2 = 99.8\%$, $P < 0.001$) (Fig. 4).

The I^2 index showed that heterogeneity among the studies assessing WPV against HCWs was very high. Based on the results

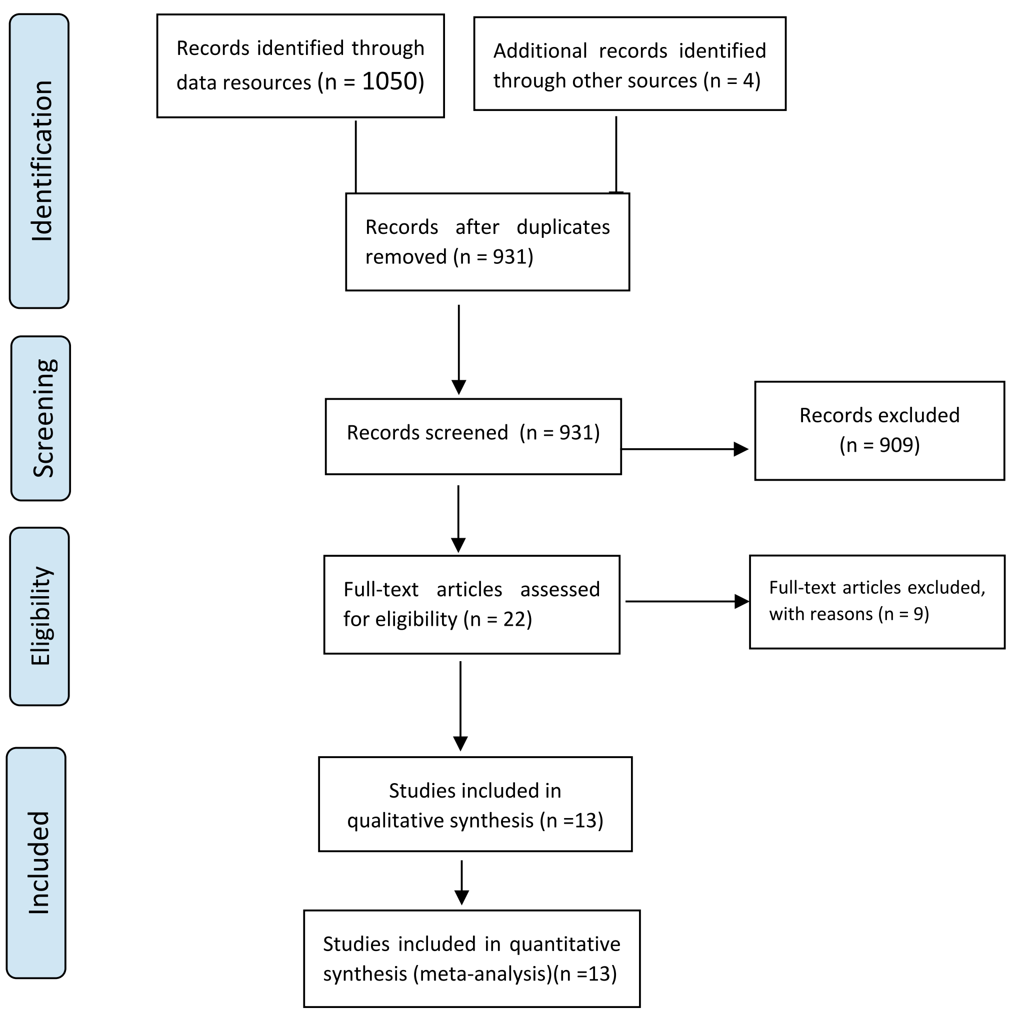

Fig. 1. Flowchart of the Selection of Studies Based on PRISMA.

Table 2
The Specifications of Studies Included in the Meta analysis.

First Author	Location	Sample Size	Male	Female	Physical	Verbal	Total of WPV	Mean age
Yang (Yang et al., 2021)	China	1063	355	708	-	-	20.4%	34.1 ± 7.2
Xie (Xie et al., 2021)	China	10,516	1653	8863	8.4%	15.8%	18.5%	33.2 ± 8.4
Mayta-Tristan (Mayta-Tristan, Alarcón-Yaquetto, & Málaga, 2021)	Peru	200	106	94	0.6%	89.9%	84.5%	37.5
Lafta (Lafta, Qusay, Mary, & Burnham, 2021)	Iraq	505	195	310	-	-	87.3%	-
Ghareeb (Ghareeb, El-Shafei, & Eladl, 2021)	Jordan	382	162	220	16%	52%	65.5%	40.24 ± 11.5
Bitencourt (Bitencourt et al., 2021)	Brazil	1166	288	878	-	-	47.6%	-
Arafa (Arafa, 2021)	Egypt	209	79	130	9.6%	-	-	28.1 ± 6.9
Yang (Yuan Yang et al., 2021)	China	15,531	1770	13,761	6.9%	16.1%	18.5%	33.42
Byon (Byon et al., 2021)	USA	373	21	352	44.4%	67.8%	-	-
Li (Li et al., 2020)	China	1103	102	1001	5.8%	27.5%	29.2%	-
Özkan (Özkan Şat, Akbaş, & Yaman Sözbir, 2021)	Turkey	263	31	232	8.4%	57.8%	-	71.33 ± 15.05
Ghanbari (Ghanbari, Panahi, & Pouy, 2022)	Iran	112	7	105	11.1%	55.7%	-	33.11 ± 5.22
Shaikh (Shaikh, Khan, Baig, Khan, & Arooj)	Pakistan	356	218	138	6.5%	33.1%	41.9%	30.17

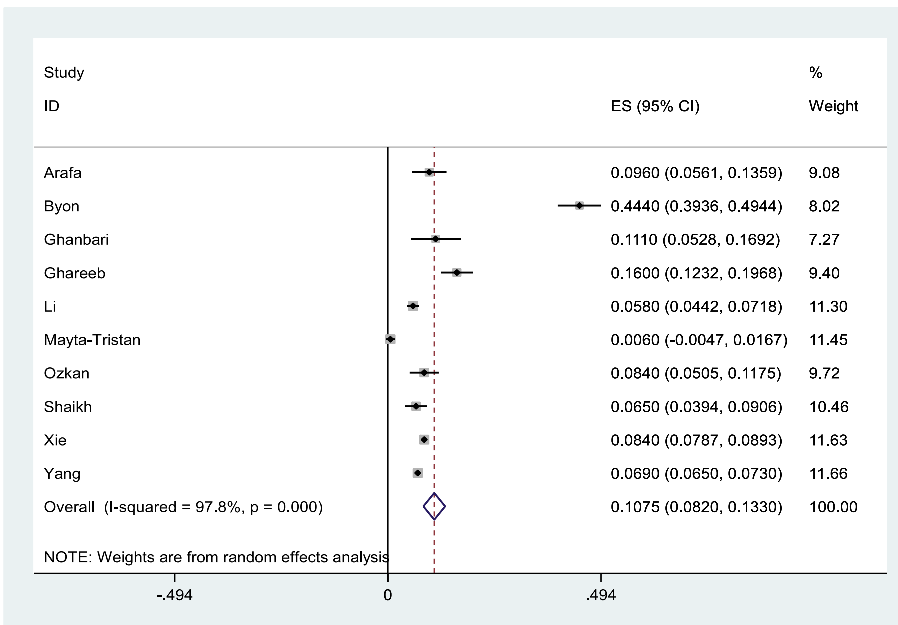

Fig. 2. The Forest Plot of Overall and Individual Prevalence of Physical WPV in the Studies with 95% Confidence Interval.

of the Egger test, publication bias was detected in reporting physical (P = 0.423), verbal (P = 0.004), and overall (P = 0.012) violence at the workplace. Publication bias was significant regarding verbal violence and overall rate of violence, but it was non-significant in terms of physical violence.

5. Discussion

In this review, the prevalence of WPV and its various forms among HCWs during the COVID-19 pandemic were investigated. Thirteen studies were selected for meta-analysis. The results of meta-analysis showed that the overall prevalence of physical and verbal WPV, as well as the overall rate of this phenomenon were 10.75%, 45.87%, and 45.80%, respectively. The results of an umbrella review study showed that the prevalence of WPV against HCWs in hospital and pre-hospital settings was 58.7% (Sahebi, Golitaleb, Moayedi, Torres, & Sheikhbardsiri, 2022). The results of a meta-analysis in 2020 showed that the overall prevalence of WPV against HCWs was 61.9%, and the rates of physical and verbal violence were 24.4% and 57.6%, respectively (Liu et al., 2019). The results of another meta-analysis in 2019 showed that the prevalence of WPV against physicians was 69% (Nowrouzi-Kia, Chai, Usuba, Nowrouzi-Kia, & Casole, 2019). A meta-analysis study in 2018 reported that the overall prevalence of WPV against HCWs in China was 62.4%, with the rates of 13.7% and 61.2% for physical and verbal violence, respectively (Lu et al., 2020). The results of a study by Sahebi *et al.* in Iran indicated that the rates of workplace physical and verbal violence against the personnel of Emergency Medical Services (EMS) were 36.39% and 73.13%, respectively (Sahebi, Jahangiri, Sohrabizadeh, & Golitaleb, 2019). A comparison between our findings and those of other studies highlights a lower average rate of WPV and its various forms during the COVID-19 pandemic than during the time before the pandemic. Thus, it seems that the COVID-19 pandemic has led to a reduction in WPV against HCWs. It should be noted that during the pandemic, health care centers have limitations on the presence of visitors and patient companions in medical wards. Also, the fear of companions contracting the COVID-19 disease contributed to their decreased presence in health centers. Therefore, lower contacts with patient companions can explain the reduction in workplace violence against HCWs during the pandemic.

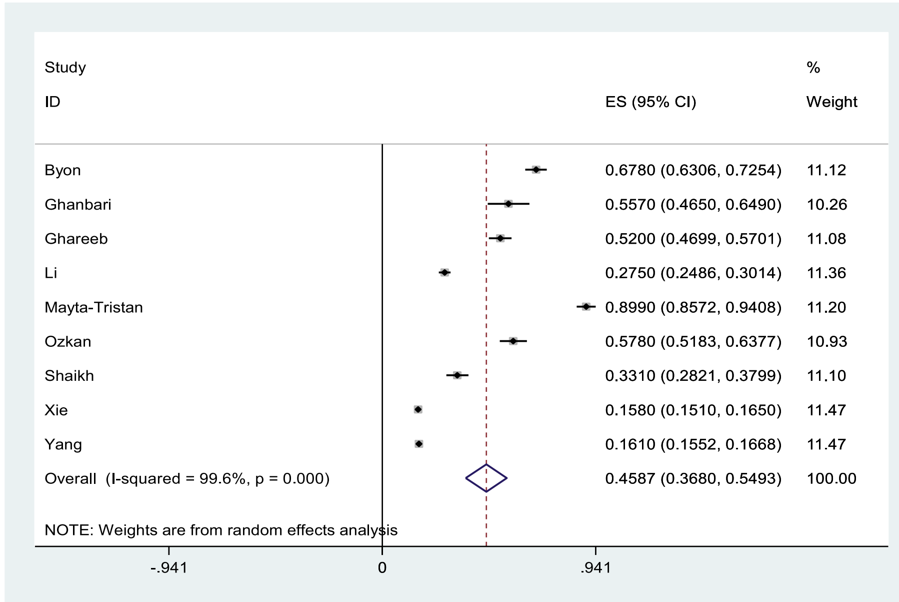

Fig. 3. The Forest Plot of Overall and Individual Prevalence of Verbal WPV in the Studies with 95% Confidence Interval.

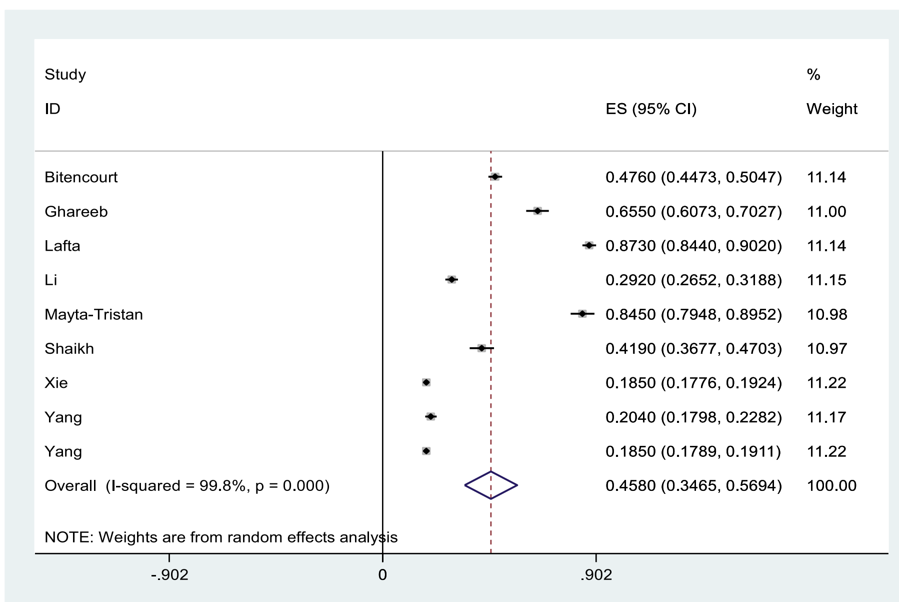

Fig. 4. The Forest Plot of Overall and Individual Prevalence of Overall WVP in the Studies with 95% Confidence Interval.

The results of a study by Abed *et al*. showed that females were more likely to experience WPV than males (Abed, Morris, & Sobers-Grannum, 2016). The results of another study showed that the prevalence of WPV was higher among female nurses than their male peers (Dehghan-Chaloshtari, & Ghodousi, 2020). Consistent with our observations, the results of these studies highlighted the role of gender differences in the incidence of WPV against HCWs. Females generally constitute a higher proportion of employees in health centers, which can justify the higher prevalence of workplace violence against them.

The COVID-19 pandemic has been one of the most stressful recent events globally, leading to numerous social challenges. HCWs were among the first groups to directly face the pandemic, causing them a great deal of anxiety, stress, work burden, and fear of the disease, as well as immense psychological pressure (Di Tella, Romeo, Benfante, & Castelli, 2020). The allocation of health care resources to confine the Covid-19 pandemic has markedly limited the availability and accessibility of health services (Garg, Basu, Rustagi, & Borle, 2020). Other studies have shown that factors such as lack of information, insufficient personnel and equipment, and inadequate communication skills can boost the risk of aggressive behaviors in health care centers (Mento et al., 2020). Based on these studies, it can be concluded that HCWs bear a great amount of psychological pressure during the COVID-19 pandemic. Since the COVID-19 disease is still spreading, it is expected that health care centers, as the forefronts of this war, will face resource shortages. Increased expectations of patients and their companions along with the aforementioned factors can increase the risk of

WPV against HCWs. Therefore, it is recommended that health managers consider physical and mental supportive measures for HCWs and regularly screen them for the signs of psychological disorders.

6. Conclusion

The results of the present study showed that the prevalence of WPV against HCWs was relatively high during the COVID-19 pandemic; nevertheless, it was lower compared to the area prior to the pandemic. Two years have passed since the start of the COVID-19 pandemic, and considering that the disease is still spreading, health care centers, the forefronts of fighting against the disease, are expected to wither in terms of staff and other resources in the long run, which may predispose HCWs to the occurrence of WPV. Therefore, health policymakers should consider full and continuous support for HCWs and regularly screening them for psychological disorders. HCWs should also be provided with ongoing education on coping strategies against stress, anxiety, and anger. Implementing organizational interventions (including policies to ensure that HCWs report WPV to their supervisors, increasing staffing per patient, and installing systems for HCWs to call for immediate assistance) can increase the resilience HCWs.

7. Strengths and limitations

The present review was the first to address the prevalence of WPV against HCWs during the COVID-19 pandemic. One limitation is the lack of separate reporting of WPV against male and female HCWs, which was not addressed by the studies reviewed. Another limitation of this study was the small number of studies included in the search time period.

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