

Title: Stepping into Safety: A Systematic Review of Extended Reality Technology Applications in Enhancing Vulnerable Road User Safety

Abstract

Purpose

In alignment with the the European Union’s Vision Zero initiative to eliminate road fatalities by 2050, leveraging technological advancements becomes crucial for addressing the challenges of vulnerable road users(VRUs), and for mitigating the impact of human error. Despite increasing scholarly interest in applications of extended reality(XR), a research gap persists, particularly in the role of XR in transportation safety. Therefore, the aim of the study was to fill this gap through a systematic literature review to evaluate comprehensively the potential scope and practical applicability of XR technologies in enhancing the safety of VRUs.

Design/methodology/approach

A systematic review was undertaken, following PRISMA guidelines meticulously, in which 80 relevant articles from databases, such as Scopus and Science Direct, were identified and analysed.

Findings

The results of the analysis revealed the potential of XR beyond pedestrians and cyclists, and highlighted a lack of research about the impact of XR with regard to the personal traits or abilities of VRUs. The results of a thorough analysis confirmed the potential of XR as a promising solution for an approach to collaborative co-creation in addressing the safety challenges of VRUs. In addition, the integration of eye-tracking with virtual reality emerged as a promising innovation for enhancing the safety of vulnerable road users.

Practical/Theoretical implications

Practically, the findings from the study offer insights to assist urban planners and transportation authorities in incorporating XR technologies effectively for VRUs safety. Identifying areas for further development of XR technology could inspire innovation and investment in solutions designed to meet the safety needs of VRUs, such as enhanced visualisation tools and immersive training simulations.

Theoretical implications include enhancing the understanding of applications of XR in VRUs’ safety and providing insights into future research possibilities and methodological approaches. Valuable insights into search strategies and inclusion-exclusion criteria can guide future research methodologies.

Originality/Value

The findings of previous research underscore the vast potential of XR technologies within the built environment, yet their utilisation remains limited in the urban transport sector. The

intricacies of urban traffic scenarios pose significant challenges for VRUs, making participation in mobility studies hazardous. Hence, it is crucial to explore the scope of emerging technologies in addressing VRUs issues as a pre-requisite for establishing comprehensive safety measures.

1. INTRODUCTION

According to the Global Status Report (2023), 1.19 million people are killed annually on roadways globally. Between 2015 and 2030, 265 million more people are expected to suffer morbidity or severe injury from traffic crashes (Eskandari Torbaghan *et al.*, 2022). According to national statistics (2023), the United Kingdom (UK) alone reported 1,760 road deaths in 2022, where the findings of studies showed that 80% of all fatalities and serious injuries were attributed to vulnerable road users (VRUs). The proliferation of complexities in urban mobility and the fatality rate give rise to an urgent need for safety solutions and action plans to be devised in order for VRUs to achieve the Vision Zero Goal of the European Union (EU) for zero fatalities on European roads by 2050 (Booth *et al.*, 2023) and, also, the Sustainable Development Goals (SDGs) of the United Nations (UN) for good health and well-being (UN SDG 3) and sustainable cities and communities (UN SDG 11) (Eller, 2022). The specific target of SDG 3 is to halve the number of global deaths and injuries from road traffic crashes (Target 3.6) and provide access to safe, affordable, accessible, and sustainable transport systems, as well as to improve road safety for all (Target 11.2) (United Nations, 2023). The targets mentioned above underpin the need to comprehend the state-of-the-art techniques employed to address the fundamental road safety challenges encountered by VRUs.

The findings of recent studies have demonstrated the adoption of profound extended reality (XR) technologies to address a range of road safety challenges involving VRUs, such as automated driving (Riegler *et al.*, 2021; Kutela *et al.*, 2022), hazard identification (Guo *et al.*, 2022), visual attention capacity (Sawitzky *et al.*, 2022), crossing decision (Bhagavathula *et al.*, 2018), behavioural study (Iryo-Asanoa *et al.*, 2018), pedestrian knowledge and behaviour

improvement (Saadati *et al.*, 2022), collision warning system (Oczko *et al.*, 2020), collision detection system (Kamalasanan *et al.*, 2022a), and education/training/awareness (Zulkifli *et al.*, 2021; Rimu *et al.*, 2022). In the studies and the resulting information, the benefit of XR in exerting sophisticated control over generated traffic conditions is demonstrated, especially while assessing VRU behaviour. Also, there could be concealed potential for increased value in mitigating road trauma through the utilisation of emerging technologies such as XR.

XR, also referred to as “cross-reality”, is an umbrella term for technologies, such as augmented reality (AR), mixed reality (MR), and virtual reality (VR), that transform reality by adding digital aspects to the physical or real-world environment to any extent (IDF, 2023) (Figure 1).

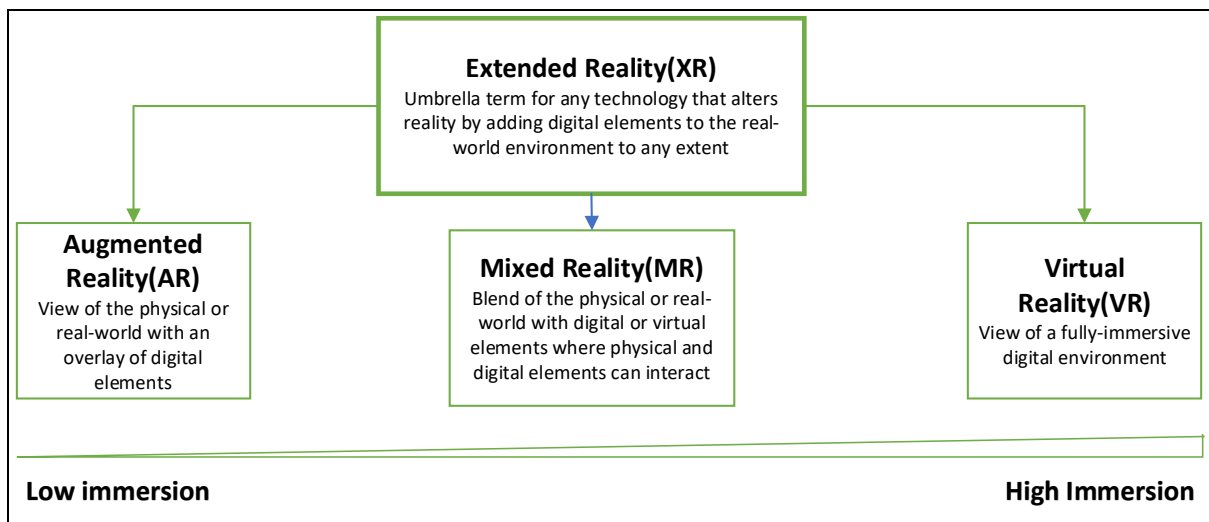


Figure 1: Extended Reality (Authors construct)

Referring to the concept of the reality-virtuality continuum of Milgram and Colquhoun (1996), Skarbez (2021) differentiated categories of XR where: AR constitutes a real environment segmented with virtual objects; VR completely immerses the participant-observer in a synthetic, digitally-generated environment; and, conversely, in MR, users should perceive that they are in an environment where real and virtual stimuli are flawlessly combined and react intelligently to user behaviour. Researchers have employed AR, MR, and VR inter-changeably to address various road safety challenges, involving VRUs, based on the precise objectives

being studied. Schneider and Bengler (2020), while investigating pedestrian behaviour, using virtual traffic scenarios, noted that VR is a secure and affordable prototype, particularly when researching vulnerable populations and emerging technology. In another study, Perez *et al.* (2019) outlined the limitations that render VR unsuitable for simulating larger, virtual scenarios and, hence, adopted the AR concept in pedestrian simulators to enable the simulation of pedestrians in a large virtual scenario such as a city. Meanwhile, Zulkifli (2021) employed AR and VR technologies to impart road safety awareness among child road users. In a different research context, Kamalasanan *et al.* (2022) were of the opinion that, compared with VR and AR, artificial experimental conditions in MR produced more realistic experiences because of the integration of virtual content and the real-world environment, and proposed a Pedestrian in-the-Loop (PIL) MR Framework in which mobile, virtual, cyclist avatars co-exist with people in a real outdoor setting.

The present study was initiated following the identification that a multitude of research studies about diverse XR technologies was already accessible, but a comprehensive examination of the possibilities to apply XR in enhancing the safety of VRUs was notably absent in the existing body of literature. The existing literature about the employment of technologies within the XR spectrum is systematically reviewed in this article in order to address road safety challenges involving VRUs to assess the scope and applicability of AR, VR, and MR technologies in enhancing the safety of VRUs. Embarking on a comprehensive study about XR applications in VRU safety can also result in evaluating the methodologies employed and objectives attained in different research endeavours, making it possible to delineate directions for future research and experimentation. To improve the transparency of the systematic review, the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) approach was adopted for the study. The PRISMA statement guides the reporting of each phase of the review process, from searching the database to analysis (Moher *et al.*, 2015).

This paper has been structured as follows: **Section 2** contains further background to the pertinence of the XR spectrum in VRU safety; **Section 3** encompasses an elucidation of the research methodologies employed in the systematic review; **Section 4** comprises the summary and interpretation of the results; **Section 5** concludes this study with an outline of emerging themes and future research direction.

2. BACKGROUND

2.1. Requisites to Safeguard Vulnerable Road Users

VRUs are defined holistically in the ITS Directive as "non-motorised road users, such as pedestrians and cyclists as well as motorcyclists and persons with disabilities or reduced mobility and orientation" (Directive 2010/40/EU, 2010). In a recent study, Booth *et al.* (2023) proposed a comprehensive classification of VRUs as part of the SOTERIA road safety project initiated by the EU, by classifying VRUs as motorised VRUs (motorcyclist, e-motorcyclist, moped user, e-moped user, e-bicyclist, e-scooterist, hover-board (Segway) user, mobility scooter user) and non-motorised VRUs (bicyclists, scooterists, skateboard users, horse/pony riders, wheelchair users, baby/toddler perambulator users, joggers, pedestrians). The timeliness, relevance, and affinity of the SOTERIA project (SOTERIA, 2023) with regard the research topic led to the adoption of this classification while developing the categorisation framework.

Considering the economic benefits (DfT, 2011), health benefits (DfT, 2017), and the government strategies to reduce emissions from road transport (The Road Safety Statement, 2019), the UK strongly advocated walking, cycling, and micro-mobility usage (The Second Cycling and Walking Investment Strategy, 2023). While the government actively endorsed active travel, the alarming fatality rate remained a substantial concern, underscoring the urgency for further actions beyond policy formulation. Among the overall VRU fatalities

reported by National Statistics (2023), pedestrians accounted for 22%, motorcyclists for 20%, and pedal cyclists for 5% of the total. Moreover, there has been a rise in the number of fatalities involving motorcyclists and e-scooters since 2019. Substantiating the official statistical report, the findings of previous studies (Shen *et al.*, 2015; Soares *et al.*, 2021; Schneider *et al.*, 2022) emphasised that pedestrians were the most vulnerable among VRUs. However, in the Sustainability Mobility for Europe Report (European on the Move, 2018), the European Commission (EC) suggested taking into account the unique requirements of VRUs and various user groups in upcoming initiatives, despite the vulnerability of the VRU category. Based on the inquiry, it emerged that the feasibility of inclusive initiatives such as the challenges of the road safety of VRUs depended on: the mode of active travel, personalised preferences (Darko *et al.*, 2021), individual abilities (Adams & Ward 2020), and gender and age attributes (Bener *et al.*, 2013). In the inquiry, the extensive research potential in this field was highlighted by examining each characteristic individually.

In previous studies, inadequate infrastructure design (Glèlè-Ahanhanzo *et al.*, 2021; Gálvez-Pérez *et al.*, 2022; Liu *et al.*, 2023; Sosik Filipino & Osypchuk, 2023), behavioural factors (Jameel & Evdorides, 2020; Mikusova *et al.*, 2021; Aziz *et al.*, 2022), ineffective law enforcement (Delaney *et al.* 2016; De Gennaro *et al.*, 2016; Makarova *et al.*, 2018), lack of awareness and effective training (Glèlè-Ahanhanzo *et al.*, 2021; López *et al.*, 2022; Scarano *et al.*, 2023), and adverse environmental conditions (Wang & Zhang, 2017; Klanjčić *et al.*, 2022; Sosik Filipino & Osypchuk, 2023) were also identified as leading causes of VRU accidents and fatalities. Collaborating with VRUs on co-designed interventions should address challenges in a holistic integration of a wide range of issues (Matthews *et al.*, 2015). The traditional methods of co-creation, with the aid of technical documentation and drawings, have limitations in communicating the spatial properties of design, such as aspects of size, scale, and configuration of spatial connectivity, to the non-expert end-user (Loyola *et al.*, 2019). The findings of the

research indicate that integrating digital innovations into road safety is an intriguing and trending research topic. Eskandari Torbaghan *et al.* (2022) critically reviewed emerging technologies, including artificial intelligence (AI), machine learning, image processing, internet of things (IoT), geographic information systems (GIS), global positioning systems (GPS), VR, simulator and big data, for assessing the application in road user behaviour, road characteristics, and operational environment analysis. Also, Hasan and Hasan (2022) evaluated the use of IoT and sensors in pedestrian safety research. In previous studies (Kalisperis *et al.*, 2006; Kuliga *et al.*, 2015; Portman *et al.*, 2015; Loyola *et al.*, 2019), the relevance of XR technologies has been noted among the myriad emerging technologies in generating a spatial perception that reflects real-life experience in physical space, combined with real-time collaboration.

2.2. Attributes of Extended Reality Enhancing User Engagement

Among the myriad emerging technologies, XR holds a predominant position, as it integrates or replicates the physical environment with a "digital twin world" that enables interaction (Vasarainen *et al.*, 2021). The near-real-life experiences provided through XR devices are logical replacements for real-life road safety scenarios. Immersion and interactivity constitute the essential elements of XR, facilitating optimal user engagement.

Immersion is the "sensation of being in an environment" that can be attained physically or mentally (Sherman & Craig, 2019). According to Vasarainen *et al.* (2021), different levels of immersion are attainable, ranging from entirely immersive systems to non-immersive. Based on the level of immersion, ImTs (Immersive Technologies) are categorised as passive virtual environment (VE), exploratory VE, and immersive VE (Prabhakaran *et al.*, 2022). Passive VE encompasses activities such as watching television, characterised as a non-immersive system. On the other hand, an exploratory VE involves interactive exploration of a 3D environment through a 2D interface, such as a monitor, referred to as a semi-immersive system. Immersive

VE denotes a synthetic environment where users can interact fully with the artificial surroundings, engaging all senses (Prabhakaran *et al.*, 2022). Slater and Wilbur (1997) identified a Sense of Presence (SoP) as a state of consciousness associated with immersive VE, where it is a sense of being in one environment despite being physically located in another (Cooper *et al.*, 2018). All XR applications offer glimpses of virtual worlds, which can be wholly immersive or merely digitally created objects that overlap with the real world. The level of immersion varies for AR, MR, and VR and depends on the device used. For example, head-mounted display (HMD)-based VR creates an authentically immersive environment through the utilisation of a genuine, stereoscopic, 3D display projected onto both eyes of the user, whereas Microsoft HoloLens, employed in MR, lies in the middle of the continuum ranging from pure “reality” to pure “virtual reality” (Milgram & Colquhoun, 1996). However, VR is frequently characterised as a source of an immersive experience with a high SoP (Whyte & Nikolic, 2018). In contrast to VR, AR has more real-world information but only a moderate or medium level of immersion (Skarbez *et al.*, 2021).

According to Pan and Hamilton (2018), the terms “interaction” and “interactivity” can apply to both user-user interaction and user-medium interaction. Interactivity offers navigational possibilities, where the user can shift perspectives, and the VE can be made up of mimic features such as lighting, vibration, wind, temperature, and pressure (Vasarainen *et al.*, 2021). Similarly, more sophisticated XR applications enable real-time modifications of the VE (Radianti *et al.*, 2020). In addition, multi-modal interaction improves the realism of XR by employing several simultaneous input and output modalities and human senses (visual, auditory, haptic, olfactory, and gustatory modalities) (Rakkolainen *et al.*, 2021).

At the technical level, AR, MR, and VR technologies rely significantly on cutting-edge information technologies, including simulation technology which contributes to refining the user experience, to ensure sustained engagement (Ke *et al.*, 2019). However, there are

differences in the level of interactivity in AR, MR, and VR. In MR experiences, users can interact with both digital and physical elements. This contrasts with AR, where digital and physical elements remain non-interactive, and VR, where the physical or real-world environment is entirely obscured (IDF, 2023).

User engagement is viewed as a favourable and perhaps indispensable human reaction to activities conducted through computer-mediated means (O'Brien & Toms, 2007). VE entails real-time interactivity by promptly detecting user input and responding instantly to the newly initiated activity, leading to enhanced user engagement (Bakar *et al.*, 2011). According to Shin (2019), the involvement of the user depends on the context, such as pre-existing conditions and personal traits and, hence, the immersion and interactivity are subject to the user's perspective. However, the immersion and interactive features of XR affect the user's performance in VE (Tzabavari *et al.*, 2015) and, therefore, XR technologies display significant potential in facilitating co-creative exploration and the assessment of user experiences.

2.3. Extended Reality Applications in the VRU Safety Realm

From the perspective of Xiong *et al.* (2021), XR, the paramount sub-set of the Reality Virtuality Continuum (RVC) (coined by Milgram and Colquhoun in 1994), is emerging as a next-generation display platform for deeper human-digital interactions because of the rapid advancements in high-speed communication and computation. The effectiveness of conventional road safety management systems is dependent mainly on human data collection, visual inspection, and subjective expert assessment, which are laborious, expensive and, occasionally, ineffectual owing to under-reporting and poor data quality (Eskandari Torbaghan *et al.*, 2022). According to Bakar *et al.* (2011), XR is considered to be a promising technology among ICT innovations with substantial potential for integration into existing road safety measures and in providing information about road safety factors, such as VRU behaviour, road characteristics, and operational environment. Moreover, simulating a realistic traffic

environment in VE allows for the active participation of road users, potentially leading to behavioural changes (Bakar *et al.*, 2011). XR provides a platform for individuals to act competently, confidently, and safely during their immersion in critical environments, especially when the actual environment poses risks (Schwebel *et al.*, 2016). This makes it particularly suitable for working with novices or those who are apprehensive about specific situations or environments. Moreover, the depiction of objects in three dimensions (3D) facilitates the exploration of spatial challenges that are difficult to comprehend in 2D media. Furthermore, as stated by White *et al.* (2023), the participatory approach using XR proves to be a valuable method for urban designers and transport planners, as this approach assists them in offering improved spatial understanding to users by, not only simulating visual and spatial aspects, but also incorporating elements of light, movement, and sound.

2.3.1. Scope of AR in the VRU Safety Realm

AR provides real-time, context-aware information to VRUs because it has the potential to deliver personalised safety alerts (Sabeti, 2023), guide users with navigation cues (Stefanucci *et al.*, 2022), and raise awareness of potential hazards in their immediate environment (Yoon *et al.*, 2014). AR integrates VR with video processing and computer vision techniques, providing an enhanced view of real scenes augmented with virtual objects. AR has the potential to captivate and inspire learners, encouraging them to delve into road safety scenarios from diverse perspectives (Baker *et al.*, 2011). It has proven to be particularly valuable in teaching subjects that students might not have the opportunity to experience first-hand in the real world (Rampolla & kipper, 2012). Furthermore, the immersive and interactive approach enables individuals to develop a deeper understanding of road safety practices and fosters a heightened sense of awareness, ultimately contributing to the reduction of accidents and promoting a safer road environment for all.

2.3.2. Scope of VR in the VRU Safety Realm

VR technology can be applied to create realistic simulations that enable users to experience and navigate various traffic scenarios, offering a safe and controlled environment by immersing them in near real-life situations (Guo *et al.*, 2022). There are seven elements of VR: simulation, interaction, artificiality, immersion, tele-presence, full-body immersion, and networked communications (Chang *et al.* 2019).

The immersion and interaction experienced within a virtual VR setting emerge as substantial indicators of user engagement. Inter-personal interactions occurring within the virtual space play a vital role in generating a positive impact on user satisfaction during a VR experience (Hudson *et al.*, 2019). This characteristic renders VR particularly conducive to fostering improved user perceptions of spaces, such as streets.

Existing research on presence in interactive VR has been concentrated predominantly on visual stimuli, with vision traditionally considered to be primary for spatial localisation and human experience. However, it is crucial to recognise that auditory cues constitute a significant aspect supporting the SoP and a sense of being in the virtual environment (White *et al.*, 2023). Ultimately, Loyola *et al.* (2019) noted that VR serves as a significant tool for designing and evaluating urban infrastructure through a participatory approach, thereby promoting the development of safer environments.

2.3.3. Scope of MR in the VRU Safety Realm

MR, that blends elements of both VR and AR, offers a dynamic platform for creating interactive and immersive environments that simulate real-world scenarios. In the context of VRU safety, MR can contribute to training programmes by providing realistic simulations of traffic situations (Kim & Rhee, 2019), enabling users to navigate and respond to various challenges in a controlled virtual space (Lee *et al.*, 2022). The integration of MR technologies can enhance user engagement and spatial understanding (Nath *et al.*, 2023), fostering a more

profound appreciation of road safety principles among pedestrians and cyclists. Moreover, MR applications can be instrumental in urban planning by simulating proposed infrastructure changes and their potential impact on VRU safety (El-Shimy *et al.*, 2015). As MR continues to evolve, its potential in the VRU safety realm holds significant promise for creating safer and more user-friendly road environments.

Cumulative evidence indicates the viability of XR as an effective tool for enhancing road safety. Several researchers have undertaken systematic reviews to investigate the application of AR, VR, and MR independently among diverse VRUs (Wynne *et al.*, 2019; Riegler *et al.*, 2021; Vankov & Jankovszky, 2021; Pavel *et al.*, 2022; Morgan *et al.*, 2023). Despite this, there is a notable absence of an integrated study in which the application of the entire spectrum of XR technologies in the VRU safety domain is addressed and evaluated comprehensively. Moreover, various XR technologies have been utilised in a limited number of studies in the context of VRU safety. This underscores the need for an investigation to determine whether the full potential of XR technologies within the road safety domain has been realised adequately in research studies. Therefore, the aim of this study was to fill this gap by systematically analysing pertinent research studies and contributing to a more comprehensive understanding of the role of XR in enhancing VRU safety.

3. RESEARCH METHODOLOGY

A systematic review was conducted, progressing through the following stages to attain the research objective of gaining insights into the application of XR technology in improving VRU safety: 1) Composition of the inclusion and exclusion criteria; 2) Identification of relevant literature; 3) Review of literature; 4) Creation of a categorisation framework; 5) Categorisation of the literature based on the framework. Furthermore, the evidence was synthesised and the results were interpreted through qualitative analysis. The qualitative data analysis assisted in identifying empirical evidence regarding the ways in which XR technologies can be adopted

to enhance the safety of VRUs. The use of systematic review, employing qualitative methods, facilitated the identification of insights from diverse studies related to the topic. This approach contributed to the accumulation of a substantial level of conceptual and theoretical development, fostering a deeper understanding that surpassed what could have been attained through an isolated study, while preserving the unique integrity of each study (Prabhakaran *et al.*, 2022).

3.1. Inclusion-Exclusion Criteria

Inclusion-exclusion criteria were developed to find research that was pertinent to the investigation. The adopted criteria, explained below, ensured an unbiased and comprehensive study inclusive of all significant articles to achieve an explicit review.

- Digital technologies are constantly evolving and being refined (Prabhakaran *et al.*, 2022), hence, it is critical to study recent literature to maintain the trustworthiness and currency of the findings. Therefore, this research included journal articles and conference papers published between 2012 and 2023 (inclusive).
- To compile a comprehensive review, literature that was focused on the application of any XR technologies (AR, VR, or MR) in enhancing the safety of VRUs was included.
- The wide range of currently published literature indicated a broad spectrum of applications for XR across various sectors. In order to optimise the research, only state-of-the-art XR pertinent to addressing the safety issues of VRUs was included.
- In order to maintain a set level of quality, book chapters, grey literature, and non-international journals were excluded.

3.2. Literature Identification Process

A four-stage methodology, following the PRISMA framework, was adopted for the process of identifying the literature, as illustrated in Figure 2 below. In Stage 1, Identifying relevant

literature from recognised databases, such as Scopus and Science Direct, based on the inclusion-exclusion criteria, constituted a fundamental and primary stage in this research. One of the largest abstract and citation databases for peer-reviewed literature, Scopus, contains over 200 million web pages, 230 million references, and over 27 million abstracts (Xiao *et al.*, 2022). A similar, top-tier database, Science Direct, includes 18 million publications from 4000 academic journals and 30 000 e-books (ScienceDirect, 2023). In addition, snowballing assisted in the identification of inclusive literature.

Cooper *et al.* (2018) recommended using a considerable keyword search to find the literature pertinent to the research topic rather than arbitrarily limiting the selection of literature. The keywords used to search for relevant articles were: ("Immersive Technology" or "Virtual Reality" or "Mixed Reality" or "Augmented Reality" or "Digital Reality" or "Cave Automated System") and ("Road Safety" or "Urban Safety" or "Safety") and ("Vulnerable Road User*" or "VRU" or "Pedestrian" or "Cycle*" or "Motor Cycle*" or "E Motor Cycle*" or "Moped" or "E Moped" or "E Bicycle*" or "E Scooter*" or "Hover Board*" or "Mobility Scooter*" or "Bicycle*" or "Scooter*" or "Skateboard*" or "Horse" or "Pony" or "Wheel Chair" or "Disabled" or "Toddler" or "Baby" or "Pram" or "Joggers" or "Pedestrian*")

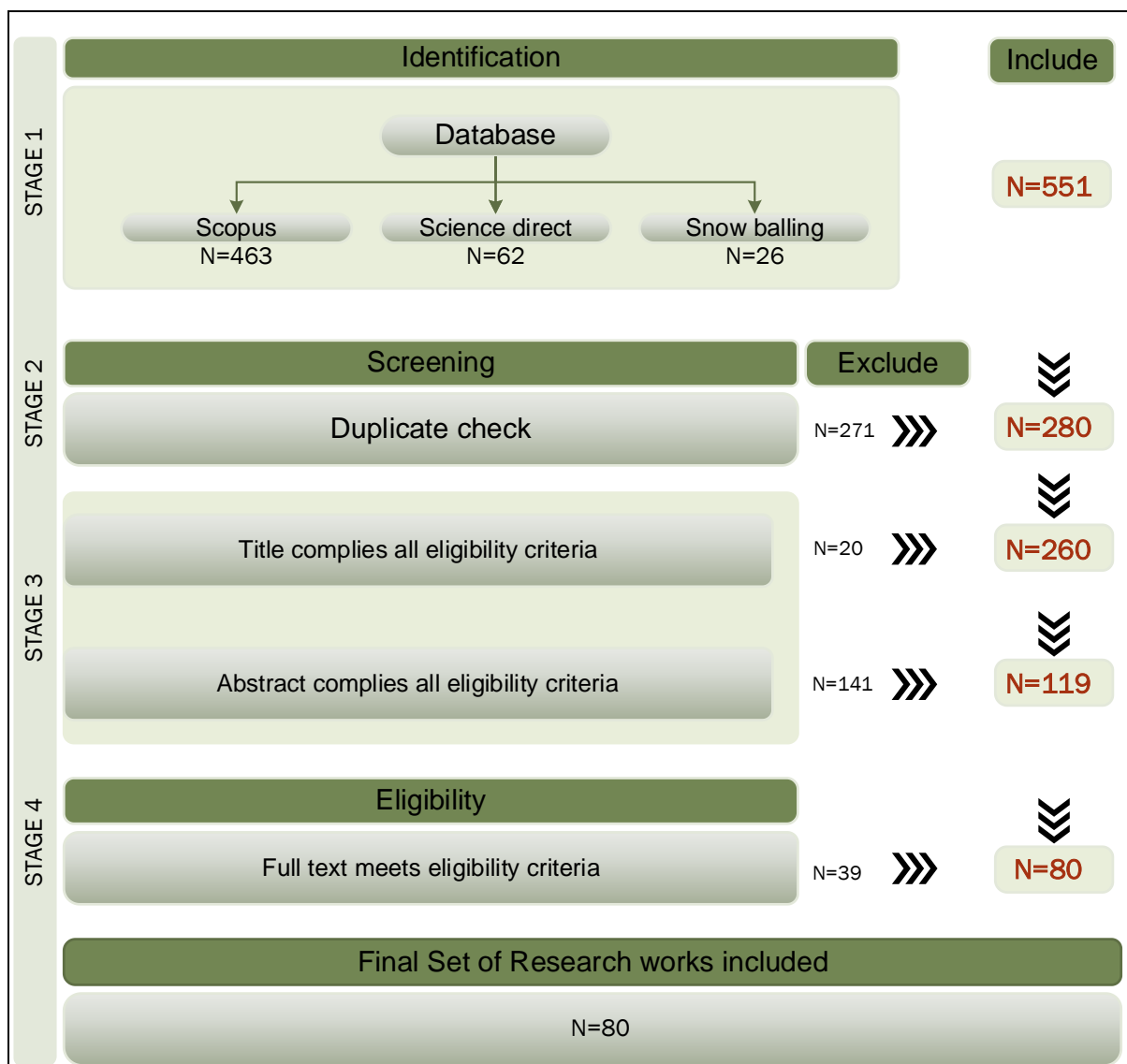


Figure 2: Literature identification process based on the PRISMA framework (Author's construct)

As shown in Figure 2, the second stage in the identification process entailed screening, with a duplication check of 551 articles, using the duplicate removal function in Microsoft Excel. Stage 3 constituted two levels of screening among the remaining 280 items of literature. Initially, the pieces of literature with titles that complied with the eligibility criteria were filtered, followed by the screening based on the compliance of the abstracts of the items of literature with the inclusion-exclusion criteria, which resulted in 119 research papers for consideration in Stage 4. Stage 4 encompassed a diligent review of the research papers by

reading the full text and excluding the literature that did not meet the eligibility criteria. Ultimately, 80 relevant pieces of literature were identified as being suitable for the systematic review, as outlined in Table 1. Considering the inclusion-exclusion criteria, journal articles (n = 60) and conference papers (n = 20) were included in the final analysis.

No.	Article Citations	Extended Reality			Road User Category
		Augmented Reality	Mixed Reality	Virtual Reality	
1	Tzanavari <i>et al.</i> (2015)			✓	Pedestrian
2	Maruhn <i>et al.</i> (2020)	✓			Pedestrian
3	Oczko <i>et al.</i> (2020)			✓	Cyclist
4	Pala <i>et al.</i> (2021)			✓	Pedestrian
5	Schneider <i>et al.</i> (2022)			✓	Pedestrian
6	Nazemi <i>et al.</i> (2021)			✓	Cyclist
7	Soares <i>et al.</i> (2021)			✓	Pedestrian
8	Bialkova <i>et al.</i> (2018)			✓	Cyclist
9	Rupi and Krizek(2019)			✓	Cyclist
10	Mantuano <i>et al.</i> (2017)			✓	Cyclist
11	Shen <i>et al.</i> (2015)			✓	Pedestrian
12	Berger and Dörrzapf (2018)			✓	Cyclist
13	Frémont <i>et al.</i> (2020)	✓			Pedestrian
14	Eyraud <i>et al.</i> (2015)	✓			Pedestrian
15	Perez <i>et al.</i> (2019)	✓			Pedestrian

No.	Article Citations	Extended Reality			Road User Category
		Augmented Reality	Mixed Reality	Virtual Reality	
16	Kim and Gabbard (2022)	✓			Pedestrian
17	Merenda <i>et al.</i> (2016)	✓			Pedestrian
18	Tabone <i>et al.</i> (2023)	✓			Pedestrian
19	Ginters (2019)	✓			Cyclist
20	Kamalasanan and Sester (2020)	✓			Pedestrian
21	Matviienko <i>et al.</i> (2022)	✓			Cyclist
22	Sövény <i>et al.</i> (2015)			✓	Pedestrian
23	Kim <i>et al.</i> (2016)	✓			Pedestrian
24	Sonntag <i>et al.</i> (2015)			✓	Pedestrian
25	Yoon <i>et al.</i> (2014)	✓			Pedestrian
26	Rusch <i>et al.</i> (2013)	✓			Pedestrian
27	Kim <i>et al.</i> (2016)	✓			Pedestrian
28	Amano and Kano (2022)	✓			Pedestrian
29	Calvi <i>et al.</i> (2020)	✓			Pedestrian and Cyclist
30	Merenda <i>et al.</i> (2019)	✓			Pedestrian
31	Zhang <i>et al.</i> (2021)	✓			Pedestrian
32	Miao <i>et al.</i> (2022)	✓			Cyclist
33	Phan <i>et al.</i> (2016)	✓			Pedestrian
34	Kamalasanan <i>et al.</i> (2021)	✓			Pedestrian

No.	Article Citations	Extended Reality			Road User Category
		Augmented Reality	Mixed Reality	Virtual Reality	
35	Amersfoorth <i>et al.</i> (2019)	✓			Pedestrian
36	Kamalasanan <i>et al.</i> (2022)	✓			Pedestrian
37	Orlosky <i>et al.</i> (2015)			✓	Pedestrian
38	Ren <i>et al.</i> (2013)		✓		Pedestrian
39	Kim <i>et al.</i> (2016a)	✓			Pedestrian
40	Kamalasanan <i>et al.</i> (2022)		✓		Pedestrian and Cyclist
41	Drechsler <i>et al.</i> (2021)		✓		Pedestrian
42	Kosch <i>et al.</i> (2022)		✓		Cyclist
43	Hartmann <i>et al.</i> (2018)	✓			Pedestrian
44	Zulkifli <i>et al.</i> (2021)			✓	Pedestrian
45	Aoyama <i>et al.</i> (2016)			✓	Pedestrian
46	Meir <i>et al.</i> (2013)		✓		Pedestrian
47	Pichen <i>et al.</i> (2020)	✓			Cyclist
48	Tabone <i>et al.</i> (2021)	✓			Pedestrian
49	Kim <i>et al.</i> (2016a)	✓			Pedestrian
50	Kanomori <i>et al.</i> (2018)			✓	Pedestrian
51	Yahaya <i>et al.</i> (2022)			✓	Pedestrian
52	Khan <i>et al.</i> (2021)			✓	Pedestrian
53	Purcella and Romijnb(2017)			✓	Pedestrian

No.	Article Citations	Extended Reality			Road User Category
		Augmented Reality	Mixed Reality	Virtual Reality	
54	Bowman and Liu (2017)			✓	Pedestrian
55	Guo <i>et al.</i> (2022)			✓	Pedestrian and Cyclist
56	Kwon <i>et al.</i> (2022)			✓	Pedestrian
57	Guo <i>et al.</i> (2023)			✓	Cyclist
58	Fratini <i>et al.</i> (2023)			✓	Pedestrian
59	Mok <i>et al.</i> (2022)			✓	Pedestrian
60	Meir and Oron-Gilad (2020)			✓	Pedestrian
61	Leon-Paredes <i>et al.</i> (2022)			✓	Cyclist
62	Sawitzky <i>et al.</i> (2020)	✓			Cyclist
63	Sawitzky <i>et al.</i> (2022)		✓		Cyclist
64	Li <i>et al.</i> (2022)	✓			Pedestrian
65	Sawitzky <i>et al.</i> (2020a)	✓			Cyclist
66	Stratmann <i>et al.</i> (2019)			✓	Cyclist
67	Bhagavathula <i>et al.</i> (2018)			✓	Pedestrian
68	Sugita <i>et al.</i> (2012)			✓	Wheelchair user
69	Matviienko <i>et al.</i> (2022a)	✓			E-Scooter
70	Iryo-Asanoa <i>et al.</i> (2018)			✓	Pedestrian
71	Wessels <i>et al.</i> (2022)			✓	Pedestrian
72	Luu <i>et al.</i> (2022)			✓	Pedestrian

No.	Article Citations	Extended Reality			Road User Category
		Augmented Reality	Mixed Reality	Virtual Reality	
73	Schwebel <i>et al.</i> (2016)			✓	Pedestrian
74	Angulo <i>et al.</i> (2023)			✓	Pedestrian
75	Deb <i>et al.</i> (2017)			✓	Pedestrian
76	Wang <i>et al.</i> (2022)			✓	Pedestrian
77	Maillot <i>et al.</i> (2017)			✓	Pedestrian
78	Cao <i>et al.</i> (2023)			✓	Pedestrian
79	Drechsler <i>et al.</i> (2022)		✓		Pedestrian
80	Devi Subramanian <i>et al.</i> (2023)			✓	Cyclist

Table 1: Articles included in the study (Author’s construct).

4. FRAMEWORK FOR CLASSIFYING LITERATURE ABOUT XR APPLICATIONS IN THE VRU SAFETY DOMAIN

4.1. Categorisation Framework

According to Urquhart *et al.* (2010), a categorisation framework based on grounded theory for categorising ICT literature has emerged as an appropriate methodology. Hence, developing a categorisation framework aligned with the aim of the research was deemed to be appropriate for this investigation. Further to the systematic identification process, the selected items of literature were grouped based on the categorisation framework. The key dimensions of the framework were determined according to the objective of the research and background study, and by reviewing the literature iteratively (Table 2).

Aspects	Definition	Category	
Target User	Category of people targeted in the study.	Motorised	Motorcyclist, E-Motor cyclist, Moped user, E-Moped, E- Bicyclist, E - Scooterist, Hover-Board user, Mobility scooter user
		Non-Motorised	Bicyclists, Scooterists, Skateboard users, Horse/Pony riders, Wheelchair users, Baby/Toddler pram users, Joggers, Pedestrians
User Category	Specific category to which each user belongs.	Children, Youth, Middle-aged, Elderly, Disabled, Cognitive, Not Specified	
Gender	User Characteristic	Unequal participation, Equal participation	
Visualisation Technology	Category of technology that substantially affects Reality via integrating digital components into the physical or real-world environment.	Augmented Reality (AR), Augmented Virtuality (AV), Mixed Reality (MR), Virtual Reality (VR)	
Technology specification	Advanced technology/device used in different	Cave, Eye tracking (ET), Head Up Display (HUD), Pedestrian cues, Head Mounted Display (HMD), Head Mounted (HM) Camera, HoloLens, AR glasses, Desktop visualiser, Wearable Haptic displays	

Aspects	Definition	Category
	visualisation technology.	
Research Method	The method adopted in each study to attain the research aim.	Case study, Experimental, Proof of concept, Literature review, Survey
Immersion Enhancement	The sensory modalities used in the experiment.	Visual, Haptic, Auditory, Olfactory, Interaction
Objectives/Utilisation Area	The research objective of the study.	Visualisation, Hazard identification, Visual attention capacity, Crossing decision, Perception of VR, environment (distance), behavioural study, collision warning system, Collision detection system, Education/training/ awareness, Cyber sickness avoidance, Gap acceptance, Virtual prototyping, safety, Accident prevention
Experiment Perspective	Participant in the experiment.	VRU, Other road users
Challenges	Challenges faced during the experiment using various visualisation technologies.	Cost, Multisensory limitations, General health and safety, Cyber sickness, technical limitation, Unrealistic effect
Collaboration and Communication in a Virtual Environment	The interactivities within the	Single-user, Distributed functionality

Aspects	Definition	Category
	virtual environment.	
Focus on the Sense of Presence	Participant's feeling of involvement.	Yes, No

Table 2: Aspects and categories of the literature categorisation framework (Author's construct)

4.2. Co-Occurrence of Keywords

According to Park *et al.* (2021), systematic keyword analysis can be used to establish thematic trends in published research because the use of keywords offers a precise and concise depiction of research content. The author keyword filtration in the VOS viewer resulted in the identification of keywords to meet the threshold. The node size, distance, and connecting lines in Figure 3 illustrate the strong connections between frequently studied keywords, while the distinct colours represent various clusters, with closely linked keywords within each cluster. The protruding AR node is evidence of the type of AR in road-safety studies. Furthermore, while behavioural control, road crossing, and situational awareness are the typical research objectives, cyclists and pedestrians are the user categories most addressed.

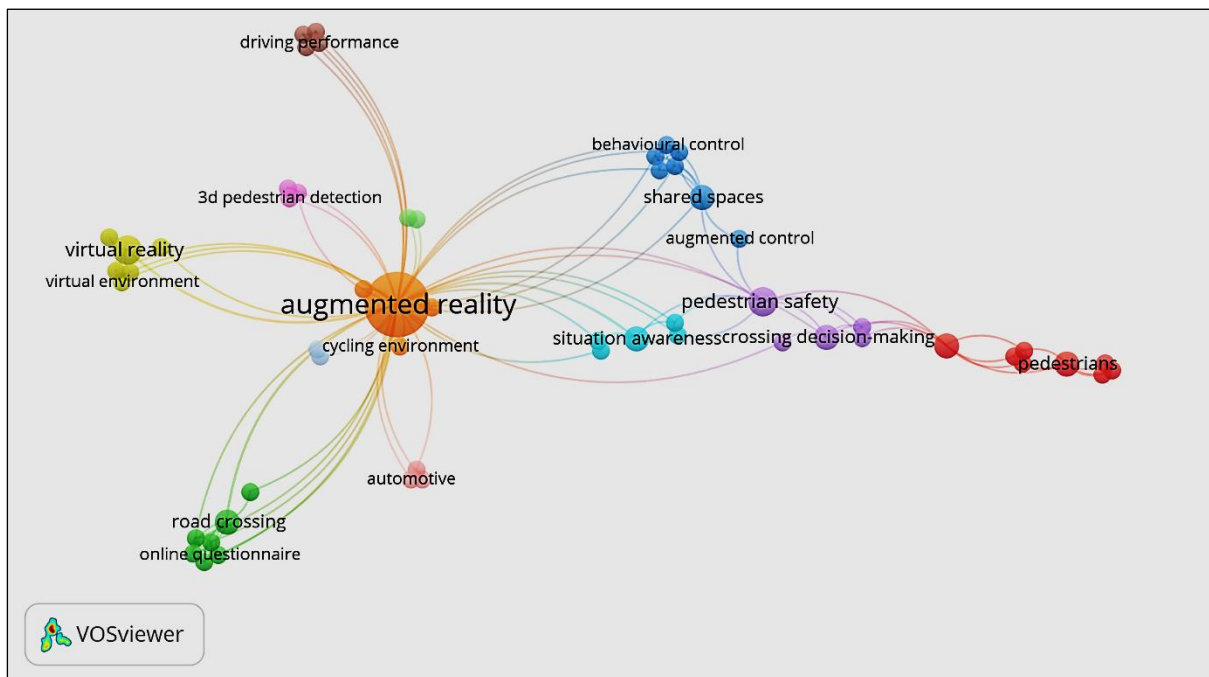


Figure 3: Co-Occurrence of keywords (Author's construct)

4.3. Citation of Articles

According to a study by Wang *et al.* (2019), articles with recent citations have higher intensities of knowledge flow. Even though the keyword co-occurrence emphasises AR, the article

citation trend in Table 3 shows that the technologies employed in the publications with higher citations are VR and eye-tracker-integrated VR.

Authors	Citation	Improvement Area	Technology used
Li <i>et al.</i> (2022)	68	Pedestrian Safety in shared space	VR
Bhagavathula <i>et al.</i> (2018)	54	Pedestrian	VR
Von <i>et al.</i> (2022)	53	Child Pedestrians and Cyclists' Safety and Improving Crossing Skills	MR
Von <i>et al.</i> (2020)	51	Cyclist	VR and ET
Von <i>et al.</i> (2020)	45	Cyclist in shared space	AR

Table 3: List of publications with the highest impact on XR-based research in road safety (Author's construct).

5. RESULTS

The surge in visualisation technologies in recent times is evident in the steep gradient of the graph (Figure 4) showing the annual publication trend of articles from 2012 to 2023. This research paper was prepared halfway through 2023; hence, the graph shows a sudden fall after 2022, as more research reports were yet to be published.

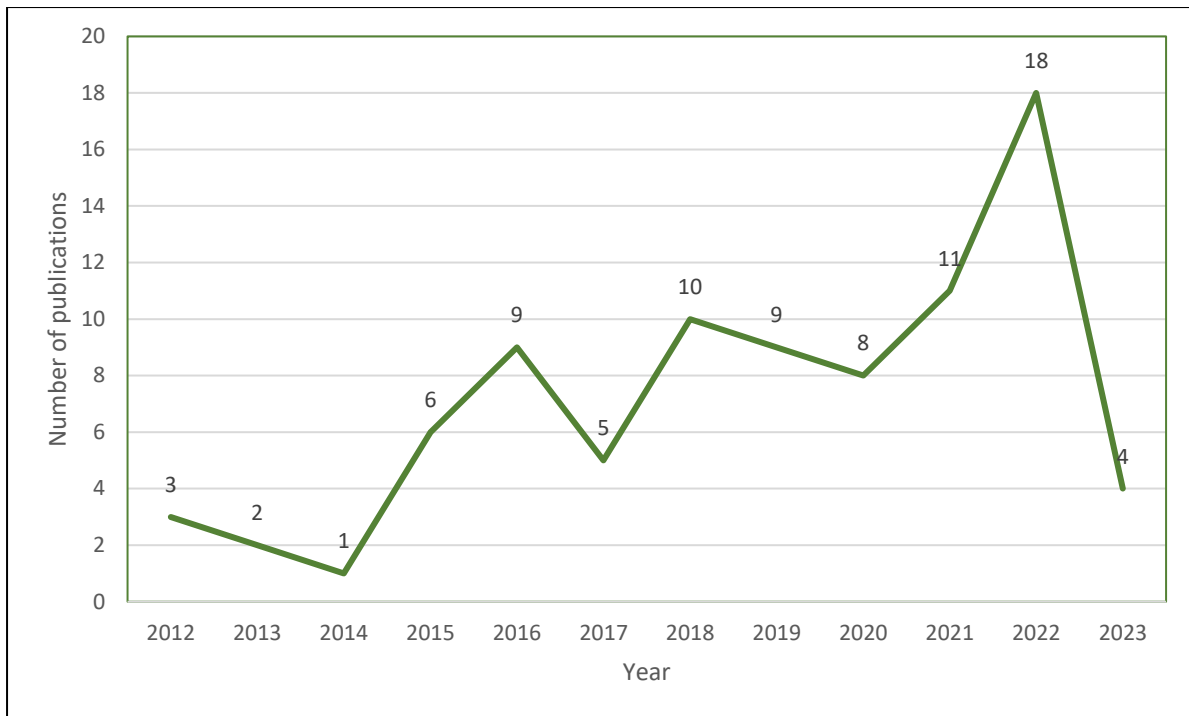


Figure 4: Annual publications from 2012 to 2023 (Authors construct)

5.1. Categorisation Based on Target Users

Since the research was focused on VRU safety, targeted users were categorised as Motorised and Non-Motorised based on the classification by Booth *et al.* (2023) (detailed in Section 2.1). The findings showed a lack of literature focused on the application of XR in the safety enhancement of all categories of VRUs. Among the studies overall, 74% were focused on pedestrian safety, 24% on cyclist safety, and the studies addressing the safety of wheelchair users, motorcyclists, and E-scooterists were only 1% each (Figure 5).

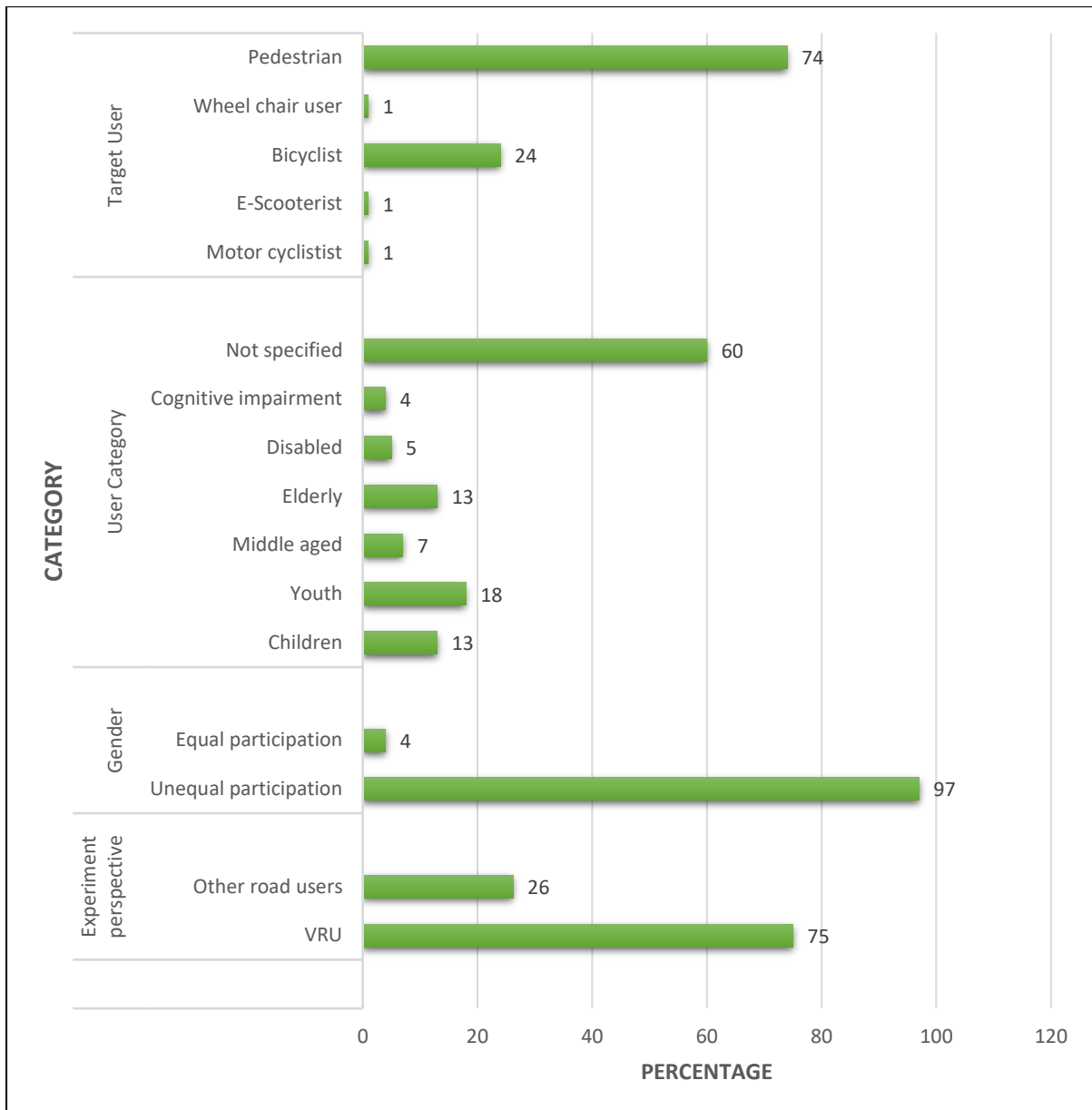


Figure 3: Article categorisation based on user (Author's construct)

According to Prati *et al.* (2019), the differences between the perceptions and attitudes of male and female cyclists towards active travel and road-user behaviours can be influenced by gender roles. However, 6% of the research was gender-neutral (Figure 5). Similarly, the road safety requirements for each age group are different. Yet, 60% of the research papers were generic, whereas 7% of the studies were focused on older adults, within which cognitive impairment issues were studied in 60%. Among the rest of the research, 13%, 18%, 7% and 5% of the

studies addressed the safety issues of children, youth, middle-aged, and disabled, respectively (Figure 5).

5.2. Categorisation Based on XR Spectrum

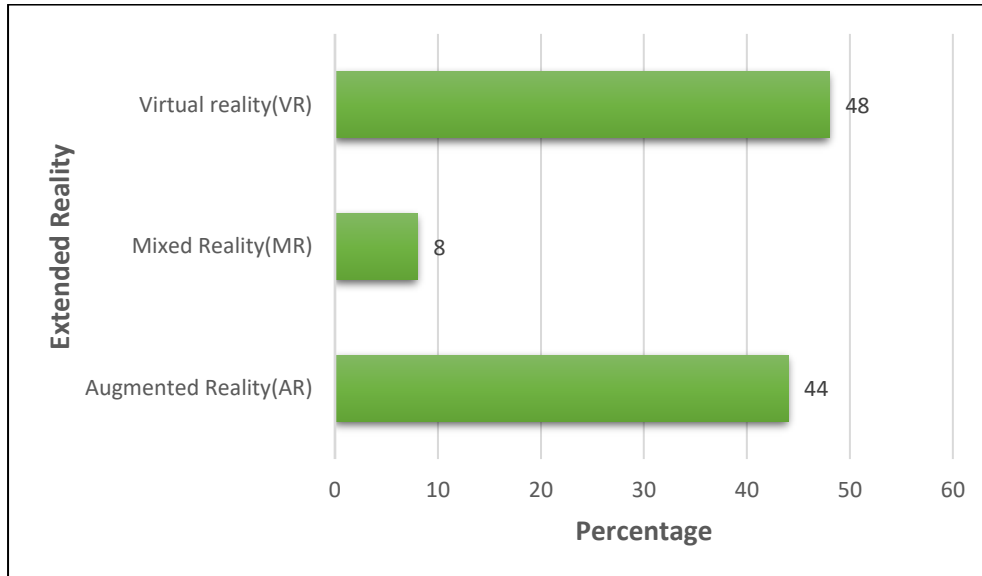


Figure 6: Article categorisation based on XR Spectrum (Author's construct)

Categorisation based on the visualisation technology indicated that state-of-the-art VR technology was adopted in 48% of the studies (Figure 6), contradicting the results in Figure 3. The contradiction arose because, as depicted in Figure 7 below, the majority of studies had embraced passive VR technology and, as a result, the term "virtual reality" was not explicitly tagged as a keyword. Only 25% of the studies involved experiments with immersive VR among the participants, whereas the rest adopted passive and exploratory techniques (Figure 7). MR and AR technologies were employed in 44% and 8% of previous studies, respectively.

Focusing primarily on pedestrians as the extensively studied target group, out of 62 research papers in which pedestrian safety issues were addressed, 29 employed AR, with 26 using AR and five experimenting with MR. In contrast, researchers addressed cyclist safety concerns in 10 out of 21 research studies, predominantly adopting VR-based experiments. In addition, MR

was incorporated in the methodologies of three research papers. According to Bogacz *et al.* (2021), engaging in cycling in an immersive virtual environment is characterised by increased involvement, signified by a higher frequency of action switches. Hence, this is the rationale for favouring VR over AR in cycling experiments.

5.3. Categorisation Based on Immersion and Interactivities

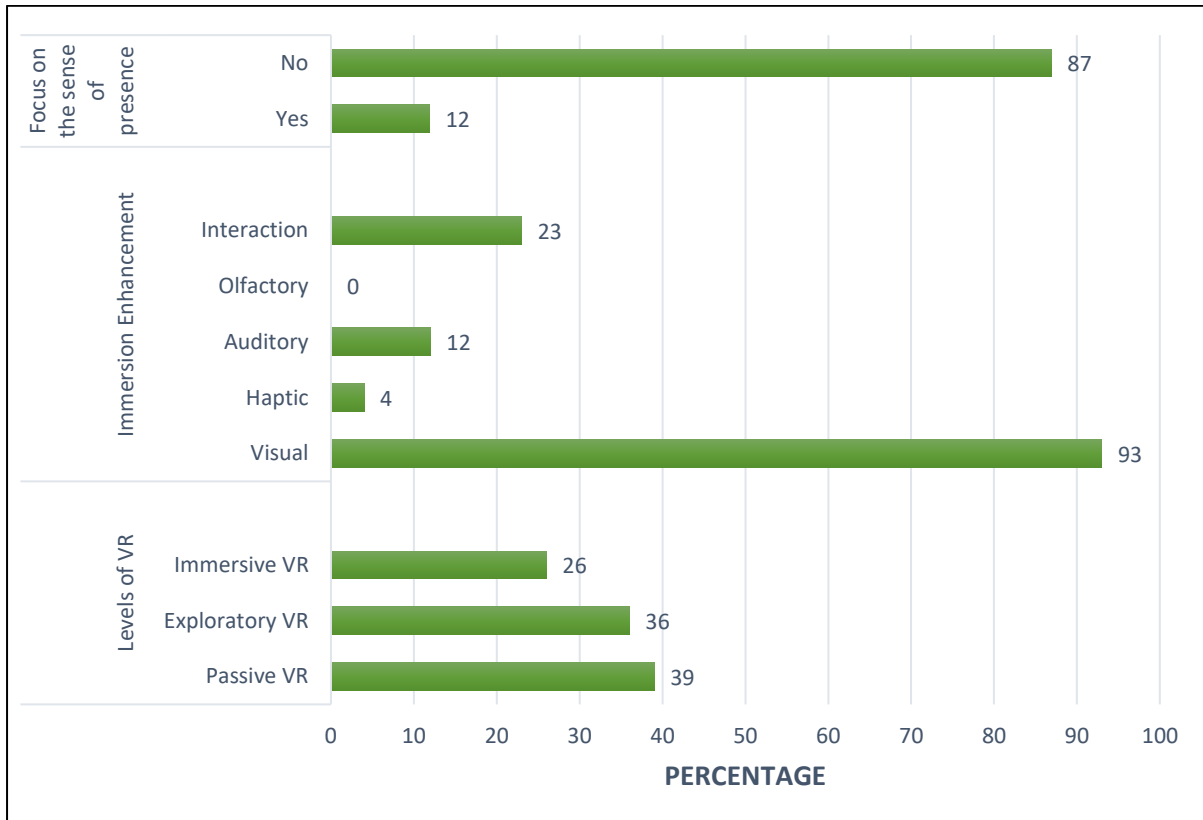


Figure 7: Article categorisation based on immersion and interaction (Author's construct)

A strong SoP is vital in improving the experience and efficiency of task-based activities in the virtual world (Lorenz *et al.*, 2018; Cooper *et al.*, 2018). Immersion, achieved through realistic visuals, sound, and other sensory stimuli, creates a convincing and absorbing virtual world. The more immersive the experience, the stronger the SoP, as users feel deeply engaged in the virtual setting. Similarly, interactivity plays a crucial role by enabling users to participate actively and manipulate elements within the virtual environment. The ability to interact with

objects, navigate spaces, and engage in activities enhances the feeling of being present in the virtual world. Real-time responses to user actions create a dynamic and responsive environment, reinforcing the SoP. However, the review data showed that the SoP factor was discarded in most of the studies (87%). Cooper *et al.* (2018) suggested that multi-modal cues, such as visual, haptic, auditory, olfactory, and virtual interaction are crucial in enhancing performance and boosting user experience and work efficiency in VE. Among the immersion enhancement factors, rather than visual cues (93%), only 23% considered interaction, whereas 12% and 8% used auditory and haptic features, respectively (Figure 7).

5.4. Categorisation Based on Research Method, Objective and Technology Applied



Figure 8: Article categorisation based on the research method and objective (Author's construct)

A categorisation of the literature based on the research methods showed that an experimental method was adopted in 83% of the research studies, with distinct VRUs as participants and appropriate virtual environment simulations to assess the application of various XR technologies in VRU safety. The experimental approach endorses systematic investigation and analysis of the impact, effectiveness, and potential applications of immersive technologies, and provides empirical evidence that contributes to a deeper understanding of how XR experiences influence various outcomes.

The tools and technologies used for each experiment vary depending on the objective of the experiment, the users, and the XR typology on which the study was focused. Head-Mounted Display (HMD) (69%) and Cave Automatic Virtual Environment (CAVE) (28%) were the prominent VR tools used in experimental studies and were focused mostly on pedestrians and cyclists. The AR-based studies that were focused on pedestrian safety, showed a need for pedestrian cues, which are provided through HUD, constituting 15% of the study. Even though highly cited (Table 3), cutting-edge ET technology has been associated with road safety assessments in few studies (1%) (Figure 8). Researchers have experimented with ET, with the aid of mobile ET glasses, in real road scenarios. ET-integrated, real-road scenarios are used mostly to assess pedestrian collisions (Yoon *et al.*, 2014; Kim *et al.*, 2018), bicycling comfort (Berger & Dörrzapf, 2018), and cyclist gaze behaviour (Mantuano *et al.*, 2017; Rupi & Krizek, 2019). Similarly, ET-integrated VR studies were minimal and focused on bicyclist and pedestrian physiological behaviour (Guo *et al.*, 2022), Psycho-physiological aspects of bicyclists have been studied to improve safety perception on curb-side bicycle lanes (Guo *et*

al., 2023), pedestrian-crossing scenarios (Fratini *et al.*, 2023), and driver-pedestrian interaction from the perspective of the driver (Mok *et al.*, 2022).

The research objectives of the scrutinised studies showed that the behavioural characteristics of VRUs were investigated in 35%. Furthermore, 25% of studies were focused on road crossing decisions, collision detection systems, visual attention capacity, and hazard identification, and 15% of the studies were focused on safety awareness among children (Figure

5.5. Integrating XR for VRU Accident Prevention

The research objectives and study contexts within the realm of XR for VRU accident prevention span a diverse array of focus areas, as described in Table 4. Behavioural aspects, such as pedestrian behaviour, assessment of cyclist comfort, and driver awareness of pedestrians are explored in AR studies. Visual attention capacity concerning the allocation of attention while driving and pedestrian-vehicle interactions are also explored. In research about hazard identification within AR, various aspects are investigated, including driver distraction and cycling quality improvement. Moreover, AR collision warning systems and crossing decisions are addressed in studies, while also focusing on education/training/awareness initiatives for children's road-safety education. MR studies encompass similar objectives but also include unique dimensions such as avoidance of cyber sickness and situation awareness, particularly in the context of developing autonomous driving systems. VR studies, on the other hand, are concentrated on crossing decisions, visual attention capacity related to virtual cycling environments, hazard identification such as pedestrian obstacles, and behavioural studies in which street-crossing behaviours among young adults and children are examined. These studies collectively contribute to advancing VRU accident prevention strategies through immersive technologies, providing insights into various facets of user behaviour, attention, and hazard perception.

	Research Objective	Study Context	Article Citation
Augmented Reality	Behavioural study	<ul style="list-style-type: none"> • Pedestrian behaviour • Bicyclist comfort assessment • Driver awareness of pedestrians • Pedestrian behaviour in shared space • Cyclist behaviour in shared space • Driver performance and behaviour • Cyclist behaviour 	Oczko <i>et al.</i> , 2020; Eyraud <i>et al.</i> , 2015; Tabone <i>et al.</i> , 2023; Matviienko <i>et al.</i> , 2022; Calvi <i>et al.</i> , 2020; Zhang <i>et al.</i> , 2021; Miao <i>et al.</i> , 2022; Amersfoorth <i>et al.</i> , 2019; Kamalasanan <i>et al.</i> , 2022; Maruhn <i>et al.</i> , 2020
	Visual attention capacity	<ul style="list-style-type: none"> • Allocation of visual attention while driving • Driver awareness of pedestrians • Pedestrian-vehicle interactions • Driver visibility improvement 	Kim <i>et al.</i> , 2019; Perez <i>et al.</i> , 2019; Kamalasanan & Sester 2020; Calvi <i>et al.</i> , 2020; Zhang <i>et al.</i> , 2021; Miao <i>et al.</i> , 2022; Orlosky <i>et al.</i> , 2015; Hartmann <i>et al.</i> , 2018
	Hazard identification	<ul style="list-style-type: none"> • Driver awareness of pedestrians • Driver distraction • Cycling quality improvement • Cyclist traffic safety enhancement • Child pedestrians hazard perception • E-scooter rider safety 	Kim <i>et al.</i> , 2019; Merenda <i>et al.</i> , 2019; Kamalasanan & Sester 2020; Rusch <i>et al.</i> , 2012; Kim <i>et al.</i> , 2018; Zhang <i>et al.</i> , 2021; Phan <i>et al.</i> , 2016; Sawitzky <i>et al.</i> , 2020; Matviienko <i>et al.</i> , 2022
	Collision warning	<ul style="list-style-type: none"> • Driver awareness of pedestrians • Driver distraction 	Tabone <i>et al.</i> , 2023; Sonntag <i>et al.</i> , 2015; Rusch <i>et al.</i> , 2012; Amano <i>et al.</i> , 2022; Merenda <i>et al.</i> , 2019; Kamalasanan <i>et al.</i> , 2021; Amersfoorth <i>et al.</i> , 2019; Kamalasanan <i>et al.</i> , 2022; Kamalasanan <i>et al.</i> , 2022; Konomori <i>et al.</i> , 2018; Sawitzky <i>et al.</i> ,

	Research Objective	Study Context	Article Citation
		<ul style="list-style-type: none"> • Pedestrian advanced collision warning system 	2020; Li <i>et al.</i> , 2022; Sawitzky <i>et al.</i> , 2020; Matviienko <i>et al.</i> , 2022
	Crossing decision	<ul style="list-style-type: none"> • Pedestrian-vehicle interactions • Pedestrian crossing decision-making at uncontrolled intersections 	Gintersa, 2019; Sövény <i>et al.</i> , 2015; Meir <i>et al.</i> , 2013; Kim <i>et al.</i> , 2016
	Gap acceptance	<ul style="list-style-type: none"> • Crossing decision-making at uncontrolled intersections 	Sövény <i>et al.</i> , 2015
	Education/training/awareness	<ul style="list-style-type: none"> • Children's road safety education 	Phan <i>et al.</i> , 2016; Aoyama <i>et al.</i> , 2016; Meir <i>et al.</i> , 2013
	Collision detection system	<ul style="list-style-type: none"> • Driver awareness of pedestrians • Enhancing drivers' perception of cyclists 	Orlosky <i>et al.</i> , 2015; Zulkifli <i>et al.</i> , 2021; Tabone <i>et al.</i> , 2021; Konomori <i>et al.</i> , 2018
Mixed Reality	Collision detection system	<ul style="list-style-type: none"> • Pedestrian-vehicle interactions 	Ren <i>et al.</i> , 2013; Kamalasanan <i>et al.</i> , 2022; Meir <i>et al.</i> , 2013
	Behavioural study	<ul style="list-style-type: none"> • Pedestrian behaviour • Pedestrian-vehicle interactions 	Kamalasanan <i>et al.</i> , 2022
	Collision warning	<ul style="list-style-type: none"> • Pedestrian-vehicle interactions 	Drechsler <i>et al.</i> , 2021
	Crossing decision	<ul style="list-style-type: none"> • Street crossing behaviour in young adults and children 	Meir <i>et al.</i> , 2013
	Education/training/awareness	<ul style="list-style-type: none"> • Child pedestrian awareness 	Meir <i>et al.</i> , 2013
	Visual attention capacity	<ul style="list-style-type: none"> • Cyclist safety awareness 	Sawitzky <i>et al.</i> , 2022

	Research Objective	Study Context	Article Citation
	Hazard identification	<ul style="list-style-type: none"> Assessing child pedestrians' hazard perception abilities 	Sawitzky <i>et al.</i> , 2022
	Situation awareness	<ul style="list-style-type: none"> Autonomous driving system development 	Drechsler <i>et al.</i> , 2022
Virtual Reality	Crossing decision	<ul style="list-style-type: none"> Street crossing behaviour in young adults and children Pedestrian crossing decision making Visually impaired people's mobility Pedestrian-vehicle interactions 	Tzanavari <i>et al.</i> , 2015; Pala <i>et al.</i> , 2021; Schneider <i>et al.</i> , 2022; Soares <i>et al.</i> , 2021; Sövény <i>et al.</i> , 2015; Purcella & Romijnb, 2017; Bowman & Liu, 2017; Kwon <i>et al.</i> , 2022; Fratini <i>et al.</i> , 2023; Mok <i>et al.</i> 2022; Bhagavathula <i>et al.</i> , 2018; Luu <i>et al.</i> , 2022; Schwebel <i>et al.</i> , 2016; Angulo <i>et al.</i> , 2023; Wang <i>et al.</i> , 2022; Maillot <i>et al.</i> , 2017;
	Visual attention capacity	<ul style="list-style-type: none"> Virtual cycling environment Cyclist-pedestrian interaction Wheelchair mobility 	Oczko <i>et al.</i> , 2020; Rupi <i>et al.</i> , 2019; Sonntag <i>et al.</i> , 2015; Stratmann <i>et al.</i> , 2019; Sugita <i>et al.</i> , 2012
	Hazard identification	<ul style="list-style-type: none"> Virtual cycling environment Visually impaired people's mobility Pedestrian obstacle identification 	Oczko <i>et al.</i> , 2020; Bialkova <i>et al.</i> , 2018; Rupi <i>et al.</i> , 2019; Sövény <i>et al.</i> , 2015; Sonntag <i>et al.</i> , 2015; Konomori <i>et al.</i> , 2018; Khan <i>et al.</i> , 2021; Purcella & Romijnb, 2017; Guo <i>et al.</i> , 2022; Guo <i>et al.</i> , 2023; Leon-Paredes <i>et al.</i> , 2022
	Collision warning	<ul style="list-style-type: none"> Virtual cycling environment Bicyclists' perceived level of safety Pedestrian in shared space 	Oczko <i>et al.</i> , 2020; Nazemiet al., 2021; Devi Subramanian <i>et al.</i> , 2023
	Behavioural study	<ul style="list-style-type: none"> Street crossing behaviour in young adults and children Pedestrian crossing decision making bicyclists' perceived level of safety Cycling behaviour 	Pala <i>et al.</i> , 2021; Schneider <i>et al.</i> , 2022; Nazemi <i>et al.</i> , 2021; Mantuano <i>et al.</i> , 2017; Shen <i>et al.</i> , 2015; Sonntag <i>et al.</i> , 2015; Orlosky <i>et al.</i> , 2015; Purcella & Romijnb, 2017; Guo <i>et al.</i> , 2022; Guo <i>et al.</i> , 2023; Fratini <i>et al.</i> , 2023; Mok <i>et al.</i> , 2022; Iryo-Asanoa <i>et al.</i> , 2018; Luu <i>et al.</i> , 2022

	Research Objective	Study Context	Article Citation
		<ul style="list-style-type: none"> • Pedestrian behaviour • Cyclist eye tracking at signalised intersections • Behaviour of elderly persons with cognitive impairments • Pedestrian-vehicle interactions 	
	Visualisation	<ul style="list-style-type: none"> • Cycling through the streetscape of a real city 	Bialkova <i>et al.</i> , 2018
	Gap acceptance	<ul style="list-style-type: none"> • Visually impaired people's mobility 	Shen <i>et al.</i> , 2015; Angulo <i>et al.</i> , 2023; Wang <i>et al.</i> , 2022
	Education/training/awareness	<ul style="list-style-type: none"> • Training children with developmental disorders • Game-Based learning strategy for children's road safety education • Sustainable road education • Community-based pedestrian safety training • Training the elderly in pedestrian safety 	Orlosky <i>et al.</i> , 2015; Yahaya <i>et al.</i> , 2022; Khan <i>et al.</i> , 2021; Bowman & Liu, 2017; Leon-Paredes <i>et al.</i> , 2022; Schwebel <i>et al.</i> , 2016; Maillot <i>et al.</i> , 2017; Tzanavari <i>et al.</i> , 2015
	Cyber sickness avoidance	<ul style="list-style-type: none"> • Sickness reduction for children's road safety education 	Yahaya <i>et al.</i> , 2022; Bowman & Liu, 2017
	Situation awareness	<ul style="list-style-type: none"> • Autonomous driving system development. 	Cao <i>et al.</i> , 2023; Devi Subramanian <i>et al.</i> , 2023

Table 4: Framework of integration of XR technology in VRU accident prevention (Author's construct)

5.6. Categorisation Based on Challenges

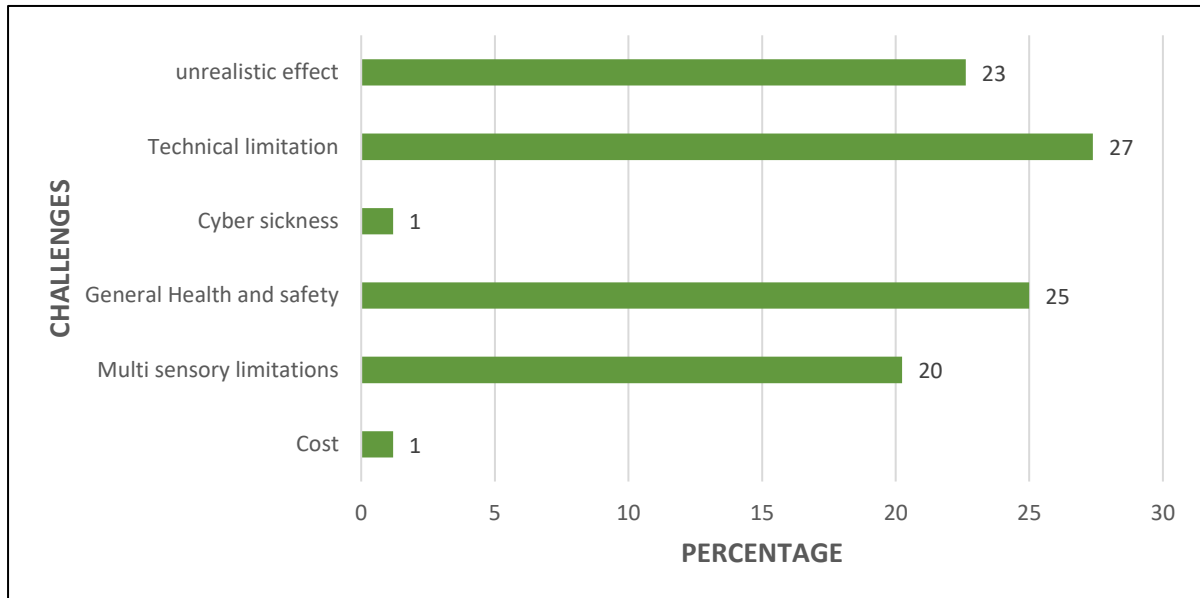


Figure 4: Article categorisation based on XR challenges (Author's construct)

Despite having valuable benefits, XR technologies have challenges such as heterogeneous users, privacy and security, and effects on health (Samal & Reva, 2022). The analysis of the articles produced nine categories of limitations, as shown in Figure 4. The results of the review showed that technical issues while adopting digital technologies were ascertained in 27 studies. The experiments conducted for 25 research studies had limitations because of general health and safety. Attempts were made by researchers, such as Yahaya *et al.* (2022), to address these issues by establishing design guidelines to reduce cyber sickness while developing VR applications for road safety awareness programmes. Simultaneously, unrealistic effects, multi-sensory limitations, and lack of immersion were the limitations encountered in the experiments for which AR was adopted.

6. DISCUSSION

In this research study, pertinent literature was systematically examined to evaluate the potential of XR technologies in enhancing the safety of VRUs, with the aim of filling the gaps in existing studies. In addition, emerging themes were identified in the study to guide future research trials in this area.

6.1. Road Safety and Targeted Road Users

Available data about road fatalities indicate that pedestrians and cyclists are the most vulnerable among VRUs. Consequently, the EC has prioritised pedestrians at the forefront of the modal priority list to improve urban road safety (Global Status Report, 2023; CARE Database, 2022). The findings of this research substantiated this, as pedestrian safety issues were addressed in most studies, with the aid of XR, followed by attention to cyclists. A significant deficiency observed pertained to the omission of specific target user categorisations, notably gender and demographic distinctions such as the elderly, youngsters, or individuals with disabilities. For instance, global statistics reveal that child pedestrians face significant risks on roads (Soares *et al.*, 2021). Similarly, gender-specific safety concerns are underscored by data which indicate that 83% of pedal-cycle casualties are male (National Statistics, 2022). Furthermore, the UK Government promotes inclusive mobility, considering the needs of individuals with disabilities and the ageing population. However, the road-safety concerns of disabled individuals are addressed in only 8% of studies, using XR technologies. Hence, there is a necessity to recognise and address the specific challenges associated with road safety for diverse user groups. Moreover, a thorough exploration of the intersection between XR technologies and the road-safety considerations linked to individual characteristics is imperative.

Several research objectives were delineated in prior studies, derived from a comprehensive background analysis. The heightened focus on addressing the behavioural characteristics of road users is attributed to the significant role that behaviour and observation play in various VRU accidents. Specifically, concerning pedestrians, behavioural characteristics emerged as a major contributing factor to road-crossing incidents (Maruhn *et al.*, 2020; Soares *et al.*, 2021). According to Schwebel *et al.* (2016), the cognitive-perceptual task of repeatedly crossing a street might result in safer pedestrian behaviour. It is challenging to accomplish such an objective through passive training or direct interference with pedestrians in complex urban environments. Thus, XR applications present the prospect of heightening awareness and refining the decision-making skills of pedestrians in road-crossing situations through the active involvement of pedestrians in virtual scenarios that closely emulate real-world behaviour. Similarly, a common contributing behavioural factor in many cyclist accidents is the absence of driver observation, as indicated by National Statistics in 2022 and, additionally, the ignorant riding behaviour of cyclists. All of these factors underscore the necessity to evaluate the psycho-physiological and behavioural characteristics of diverse road users. The environmental, socio-demographic, and situational factors also exert an influence on behavioural factors (Soares *et al.*, 2021). A proficient road user must be able to comprehend such a complex traffic environment, evaluate moving objects, and make appropriate decisions to navigate safely. Achieving such training and assessment is almost impossible through video-based awareness programmes, which underscores the significance of XR applications in this context.

6.2. Extended Reality Spectrum in VRU Accident Prevention

The synergy between XR technologies and VRU accident prevention presents a promising avenue for applying cutting-edge solutions to create safer and more informed road environments. These advancements have the potential to reduce accidents involving VRUs significantly and contribute to the overall improvement of road safety. The analysis of the

framework for integration of XR in VRU accident prevention (Table 4) showed the leading indicators of XR applications as described below.

6.2.1. Key Indicators of AR Application in Enhancing VRU Safety

AR technologies facilitate safer environments for conducting research, teaching, and training in road safety while, also, simplifying data collection and scenario control. AR technology presents a transformative approach to understanding and improving various aspects of pedestrian and cyclist interactions within urban environments. By applying AR, researchers can conduct comprehensive analyses of pedestrian behaviour across diverse settings and among diverse user groups, such as the elderly, disabled persons, children and people with cognitive disorders, providing insights into factors such as traffic flow, congestion patterns, and safety concerns. Similarly, AR enables the assessment of bicyclist comfort levels, offering valuable data for urban planners and infrastructure developers to create cyclist-friendly environments. Furthermore, AR can be used to enhance driver awareness of pedestrians on the road, potentially mitigating accidents and improving overall road safety. In shared spaces, AR simulations can be used to facilitate the study of pedestrian and cyclist behaviour, informing strategies for optimising these areas for harmonious co-existence. Moreover, AR-based studies can be undertaken to evaluate driver performance and behaviour, providing valuable feedback for enhancing road-user safety and efficiency. The conventional methods of road-safety education often fall short in reaching VRU groups effectively, lacking practicality and a structured approach. However, the emergence of AR technology has revolutionised road-safety education and training. By providing interactive experiences, AR has shown promise in enhancing safety awareness and fostering positive attitude changes (Bakar, 2011). Overall, AR emerges as a powerful tool for comprehensively analysing and improving the dynamics of pedestrian, cyclist, and driver interactions in urban environments.

Despite its numerous advantages, a significant challenge lies in achieving adequate realism, as inaccuracies in AR simulations could mislead users and compromise research outcomes. Also, the challenge of maintaining user immersion remains another notable drawback of AR-based HUDs (Skarbez *et al.*, 2021). Despite this limitation, the integration of XR with multi-modal cues and emerging technologies continues to redefine safety standards in the transportation domain.

6.2.2. Key Indicators of MR Application in Enhancing VRU Safety

MR technology offers unprecedented opportunities for analysing and improving pedestrian-vehicle interactions in real-world contexts. By employing MR, researchers can observe and analyse the dynamics of pedestrian-vehicle interactions in various scenarios, providing valuable insights for enhancing road safety measures. Similarly, MR simulations enable the investigation of interactions between cyclists and pedestrians, aiding in the development of strategies to mitigate conflicts and improve co-existence on urban streets. Furthermore, MR-based collision warning systems hold promise for improving pedestrian and vehicle safety by providing real-time alerts and interventions to prevent collisions. In addition, MR facilitates the analysis of street-crossing behaviour across different demographic groups, informing targeted interventions and infrastructure improvements. Moreover, MR-based training programmes offer innovative approaches to enhance child pedestrian awareness and safety, equipping them with essential skills and knowledge for navigating streets safely. Overall, MR emerges as a powerful tool for comprehensively studying and addressing various aspects of pedestrian-vehicle interactions to create safer and more inclusive urban environments.

Despite its potential to enable simultaneous interaction with both physical and digital objects, thereby enhancing the SoP and immersion while offering greater flexibility and adaptability,

the overall review indicated minimal utilisation of MR in the VRU safety domain. A notable design issue in MR is the "keyhole effect", which narrows the observer's field of view (FOV) akin to peering through a keyhole (Milgram & Colquhoun, 1996). While this perspective might offer precise local guidance and control, unfortunately it hampers overall situational awareness. In addition, distortion can occur when the sampled data content is projected onto the video window, leading to inconsistencies in perspective. Moreover, reversals pose challenges when triggering control actions that oppose the appropriate action at a given time. The findings of a recent study by Filipenko *et al.* (2020) highlighted several limitations of MR holograms, including limited FOV, issues with user interface design, difficulties in multi-modal interaction, concerns of comprehensibility, tracking safety, robustness in dynamic environments, and performance issues. These challenges underscore the need for further refinement and development in MR technology to address these short-comings and maximise its effectiveness in enhancing VRU safety and awareness.

6.2.3. Key Indicators of VR Application in Enhancing VRU Safety

VR technology presents innovative solutions for enhancing pedestrian mobility, safety, and education in urban environments. VR platforms offer a unique opportunity to assess and improve mobility for visually-impaired individuals and pedestrians by creating immersive virtual environments that simulate real-world challenges and scenarios. Moreover, VR simulations enable the thorough analysis of pedestrian-vehicle interactions, providing insights to enhance safety measures and infrastructure designs. In addition, cyclists' perceptions of safety in shared spaces can be explored in VR-based studies, informing strategies to improve bicyclist safety. Furthermore, VR simulations enable the analysis of elderly pedestrian behaviour, focusing particularly on individuals with cognitive impairments, to develop customised interventions for safer mobility. Moreover, VR-based game-learning strategies offer engaging and effective road-safety education, catering for children and individuals with

developmental disorders, ultimately contributing to creating safer and more accessible urban environments for all pedestrians.

However, many of the existing studies rely on passive VR experiences with limited interactivity, which diminishes the SoP for participants and restricts immersion (Whyte & Nikolic, 2018). Although immersion and interaction are deemed to be crucial components of XR (Skarbez *et al.*, 2021), the full potential of VR and XR remains largely unexplored.

VR platforms effectively address the shortcomings of MR and AR, offering high levels of immersion and minimal awareness of the external environment. This heightened immersive experience is a hallmark of VR technology and is widely recognised among XR technologies. The efficacy of VR is attributed to its ability to engage multiple senses simultaneously, providing real-time feedback and facilitating behaviour modification. Moreover, VR interventions for road safety have garnered support from EU funding initiatives (Vankov & Jankovszky, 2021). The enhanced SoP in VR environments stimulates decision-making skills and promotes heightened awareness of potential road-safety risks (Maruhn *et al.*, 2020). VR technology offers a potent tool for studying VRU behaviour and enhancing subjective comprehension and perception of hypothetical designs, while controlling contextual variables (Nazemi *et al.*, 2021).

In addition, advancements in wearables, such as smart bands, smartwatches, and eye trackers enable the tracking of human perception and behaviour in VR environments (Berger & Dörrzapf, 2018). Research efforts have led to the development of novel technologies such as collision warning systems (CWS) for cyclists, utilising sensory warning signals to improve VRU safety (Oczko *et al.*, 2020). Moreover, VR excels in precision, tracking area, field of view

(FOV), and resolution, compared with AR and MR (Maruhn *et al.*, 2020). VR's unique features, including visual, haptic, auditory, olfactory, and interactive elements, enhance the immersive experience for users (Orlosky *et al.*, 2015b).

Despite distinct features and applications, the research objectives of adopting XR visualisation technologies often overlap. Therefore, AR, MR, or VR can be utilised inter-changeably, depending on the objectives of a study. Ultimately, XR technologies with higher immersion and multi-modal interactivity offer practical solutions for achieving research objectives in the field.

6.3. Emerging XR Technology and Future Research Direction

The citation of articles (Section 4.3) reveals a preference for VR technology in highly-cited publications. The characteristics of VR, particularly suitable for experimental studies, address the limitations of immersion and interactivity often found in AR and MR technologies when assessing the behavioural aspects of VRUs. Furthermore, leveraging VR with higher SoP is essential to exploit the potential of XR fully. The extensive use of VR in education is broadly supported in literature, demonstrating its positive effects on cognition and behavioural skills. The sensory features and wide range of interactive capabilities within VR environments provide near-real-life experiences, while maintaining the integrity of road-user behaviour.

According to Berger and Dörrzapf (2018), traditional methods of collecting data about travel behaviour are enhanced by the integration of new sensor technologies. In addition to GPS tracking and crowd-sourcing of data from social media, emerging methods, such as eye-tracking (ET) technology, including Tobii Glasses, incorporate human perception and emotion into the data collection process (Kanjo *et al.*, 2015). Research about ET-integrated VR as a trending domain in VRU safety is highlighted in the literature, yet, a comprehensive

integration of human perception into data collection remains a challenge (Berger & Dörrzapf, 2018). Even though highly cited, there is presently a limited amount of literature on ET-integrated VR, indicating a need for further experimentation and trials.

However, motion sickness induced by VR, a common limitation in ImTs utilising HMDs, suggests reduced adoption of HMDs in VR experiments, especially in research involving children (Hamad, 2021). As outlined in the challenges section (Section 4.8), technical limitations often hinder experiments. Nevertheless, the novelty and capabilities of VR continue to attract researchers from diverse disciplines (Vankov & Jankovszky, 2021); hence, it demonstrates a greater potential to support future research.

Furthermore, employing VR in participatory design for programmes to prevent accidents involving VRUs offers distinct advantages over AR or MR technologies. VR provides an immersive and realistic simulation environment that enables participants to engage fully with, and understand, potential road-safety interventions. Furthermore, it assists in the evaluation of novel road infrastructure designs, safety features, and transportation policies prior to implementation, thereby potentially mitigating risks for VRUs. Different from AR, which overlays digital elements onto the real world, and MR, which blends virtual and physical environments, VR creates a completely virtual space where users can explore and interact without distractions or limitations imposed by the physical world. This immersive experience enables VR participants to focus solely on evaluating design options and potential hazards without the constraints of their immediate surroundings. In addition, VR offers a higher level of control and precision in simulating complex traffic scenarios and infrastructure designs, allowing for more accurate assessments and informed decision-making during the participatory design process. By applying the unique capabilities of VR, participatory design efforts can

achieve greater depth and effectiveness in identifying and implementing measures to improve road safety for VRUs.

7. CONCLUSION AND RECOMMENDATION

In this systematic literature review, conducted following the PRISMA method, 80 pieces of literature in which the safety concerns of VRUs are addressed through visualisation technologies within the XR spectrum were examined thoroughly. The findings of the review highlighted various XR applications, including visualisation, hazard identification, visual attention capacity, crossing decision-making, behavioural studies, collision warning/detection systems, education/training/awareness, gap acceptance, situational awareness, and virtual prototyping. Researchers utilised AR, MR, and VR inter-changeably based on the research objectives and target users.

The primary distinction between AR, MR, and VR lies in their approach to blending the real and virtual worlds, as well as the devices used. VR, with its higher SoP and multi-modal interaction capabilities, offers superior immersion compared with AR and MR. These attributes make VR exceptionally suitable for assessing the behavioural aspects of road users and suggest its potential as a robust tool for participatory design, free from physical constraints. In addition, the incorporation of novel technologies, such as ET for real-time measurement of eye movement can enrich data collection about physio-behavioural characteristics.

However, limitations in existing literature were noted in the review, including a focus on a limited sub-set of VRUs and a lack of consideration for personal traits such as gender, age, or physical and mental abilities. Based on the intense analysis, it is recommended that the research scope be broadened to include diverse VRU categories and distinct personal traits.

Furthermore, incorporating advanced VR technology with multi-modal interaction and ET integration is recommended for robust data collection.

Despite this, the study's limitation lies in its timeframe, potentially missing recent advancements in XR technology applications for VRU safety enhancement and the broad inclusion of XR and VRU categories, posing challenges in synthesising findings.

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