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EXPLORING THE IMPACT OF VIRTUAL REALITY TECHNOLOGY ON CYCLING SAFETY EDUCATION FOR PRIMARY SCHOOL CHILDREN: A SCOPING REVIEW

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ABSTRACT

Cycling safety education is becoming increasingly important, particularly for primary school children who are especially vulnerable on the roads. As road networks expand and active transportation is encouraged as a sustainable option, ensuring children can cycle safely has emerged as a critical public health and educational concern. The initiation of virtual reality (VR) technology provides a valuable tool to enhance cycling safety education by creating immersive and interactive environments where children can safely and engagingly practice essential cycling safety skills. The application of VR in cycling safety education offers plentiful advantages that align with educational, technological, and safety objectives. It fosters experiential learning, enhances engagement, improves knowledge retention, and allows children to encounter real-world traffic hazards without any actual risk. These benefits position VR as a significant teaching resource with the potential to transform early road safety education. Following PRISMA guidelines, this scoping review utilised the SCOPUS and WoS databases to systematically map the literature on VR-based cycling safety education for primary school children. It identifies key themes, evaluates reported impacts, and highlights areas for future research aimed at creating VR interventions that are age-appropriate, culturally sensitive, and technically feasible.

1. Introduction

Cycling is promoted as a sustainable and healthy mode of transportation by all parties, especially regarding cycling safety for primary school students (van Paridon et al., 2021). Integrating digital technologies into education worldwide encourages pedagogical innovation and greater international commitment to the United Nations Sustainable Development Goals (SDGs), especially Goal 3 on Good Health and Well-being and Goal 4 on Quality Education. In this context, virtual reality (VR) in bicycle safety programs provides a unique solution to the dual goals of promoting active transportation and saving children's lives. Despite these

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benefits, riding safety for primary school students remains a concern that requires global and local solutions.

Global road traffic accident data highlight the seriousness of this issue. A Statement from the World Health Organisation (WHO, 2023) mentioned that about 1.19 million people die in road traffic accidents each year, involving children and adolescents aged 5 to 29 years. Road traffic accidents are now the leading cause of death in this age group, and vulnerable road users such as cyclists and pedestrians account for more than half of the recorded deaths. On average, almost 500 children die every day in road traffic accidents, which provides a significant reminder of the risks inherent in everyday mobility. Collisions with vehicles are among the three leading causes of death among children aged 5 to 14 years (Ozturk, 2022). The developmental stage of children is closely linked to their limited cognitive maturity, lack of experience with the traffic situation and underdeveloped hazard perception, which has reduced their ability to manage road risks effectively. Traditional road safety education methods, whether through classroom lectures, video presentations or supervised on-road training, are still immature in equipping children with the situational awareness needed for real-world safety (Zulkifli et al., 2021).

1.1 Limitations of Present Road Safety Education and Logistical Challenges

These pedagogical weaknesses combine practical and logistical challenges. Cycling safety programs are often affected by external factors such as adverse weather, traffic control issues and resource constraints (Lee et al., 2022). At the policy level, the United Nations Decade of Action for Road Safety has set a target to halve road deaths by 2030, emphasising the need for innovative and scalable solutions. This reality illustrates the challenge of the urgent demand for effective safety education and the fact that existing methodologies still have limitations in replicating the complexity of real-world traffic environments. Moreover, among adolescents and young adults in Malaysia, knowledge does not always translate into safe behaviour, and many students lack a complete understanding of road signs and rules (Ismail et al., 2023; Rahman et al., 2021).

1.2 Virtual Reality (VR) as an Innovative Educational Tool

Virtual Reality (VR) has emerged as a transformative educational device that can bridge the gap between classroom instruction and real-world exposure to hazards. By engaging children in an interactive virtual world, VR offers opportunities for experiential learning without exposing them to physical hazards (Vuorio, 2024). From using headsets to advanced cycling simulators, VR technology creates realistic traffic scenarios and allows children to practice responding to hazards that cannot be ethically recreated on the road. In addition, VR also integrates cognitive, emotional, and behavioural dimensions of learning as shown in Figure 1 to create a participatory environment that increases engagement and knowledge retention compared to traditional instruction (Seo et al., 2021).

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1.3 Evidence of Effectiveness from Empirical Studies

The educational value of VR in road safety is supported by empirical evidence. A study by van Paridon et al. (2021) mentions that cyclists' behaviour in a VR hazard perception simulator can replicate their real-world actions, ensuring the validity of VR as a proxy for real-world situations. Similarly, Khan et al. (2021) reported that primary school children who experienced 3D VR/Kinect games showed measurable improvements in road crossing behaviour. Meanwhile, studies using 360° video and low-cost viewers, such as Google Cardboard, have shown parallel gains in helmet use and increased hazard awareness among students following VR-based technologies (Lee et al., 2022; Vuorio, 2024). These findings are consistent with broader educational research and highlight the benefits of participatory and interactive technologies for improving knowledge and behaviour.

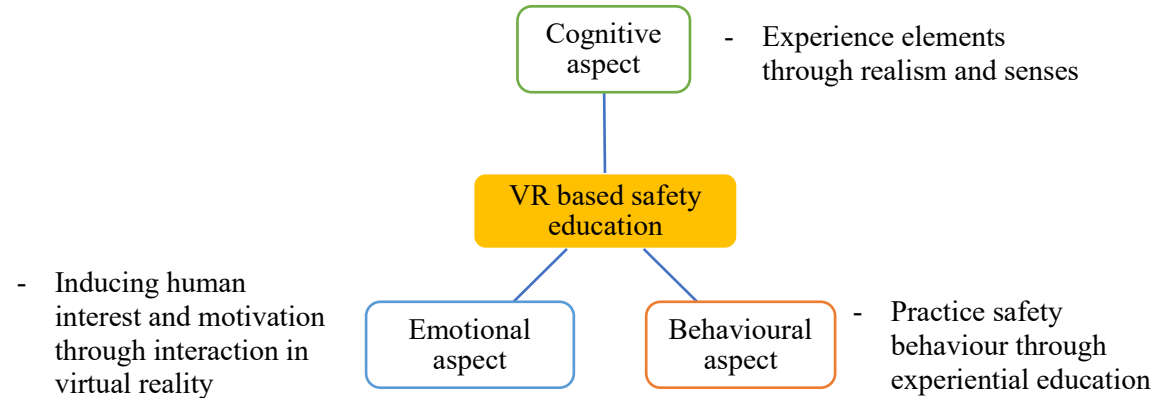

Figure 1. VR-based safety education.

1.4 Remaining Gaps and Research Needs

Most current research is based on small-scale simulations or pilot studies prioritising feasibility over long-term effectiveness (Lee et al., 2022). There is still much uncertainty about whether the behavioural changes are sustainable, as many studies only track outcomes over short periods and do not link their interventions to actual reductions in injuries. Moreover, some children feel uncomfortable or experience cyber-sickness while using VR, raising significant concerns about how comfortable and safe these systems are and the need for proper supervision (Bexson et al., 2024; Vuorio, 2024). It is prominent that more than 90% of child road deaths occur in low and middle-income countries (UNICEF, 2025), with most VR interventions having been developed and tested in high-income countries. This discrepancy reveals a significant gap in research, particularly in areas most affected by child cyclist deaths, but that have received little attention in VR safety education research.

This study focuses on VR gears as a potential aid to improve children's cycling safety awareness and behaviour. However, it also reveals significant limitations, including mixed evidence, small sample size and geographical imbalance. These gaps highlight the importance of synthesising existing findings to give educators, researchers and policymakers a clear understanding of what VR can deliver. By conducting a scoping review, the study identified

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previous research on VR-based cycling safety education for primary school children, key themes, and highlighted areas for future research proposals. It can contribute to global and local discussions on innovative educational technologies to help protect the most vulnerable road users. This work is organised into four sections: Section 1 is a literature review of cycling safety education through virtual reality, followed by Section 2, which describes the scoping review procedure, and Section 3 discusses the results. Section 4 will discuss limitations, future research suggestions, implications and conclusions.

2. Methodology

A scoping review is a method of analysing the scope of existing research to find gaps in the literature that need additional exploration. This scoping study follows Tricco et al. (2018) on Preferred Reporting Items for Systematic Reviews and Meta-Analysis for Scoping Studies (PRISMA-ScR) criteria. This study aimed to synthesise the available scientific literature on the use and impact of virtual reality (VR) technology in cycling safety education for primary school children. The scoping review method was chosen due to the experimental character of the area and the vast range of study kinds, VR formats, and evaluation of results.

The scoping review is valuable for synthesising and developing the emerging research. It clarifies conceptual boundaries, highlights trends, and maps existing evidence, informing future research directions (Munn et al., 2018; Tricco et al., 2018). In contrast, systematic reviews typically require focused questions, strict methodological criteria, and scoping reviews offer greater flexibility, incorporating a broader range of studies, designs, and contexts (Peters et al., 2015; Arksey & O'Malley, 2005). This study used the six-stage scoping review methodology developed initially by Arksey and O'Malley (2005) and later refined by Levac et al. (2010), as described below:

Step (1): Differentiating questions were formulated to demonstrate a range of evidence and provide an overview of how VR is being used globally in child-focused cycling safety education, which is the main topic of this research paper. The following research questions are presented so that a broader range of literature may be gathered: Essentially, the key questions are: What are the effects of virtual reality technology on cycling safety education? What are the themes of virtual reality in the context of cycling safety education? What is the nature of the existing scientific literature on virtual reality technology among primary school children in cycling safety education?

Steps (2): Classify past research relevant to the objectives of the scoping review. A structured search was performed utilising two prominent indexing databases: Scopus and Web of Science (WoS). These databases were chosen for their stringent indexing criteria and extensive coverage of high-quality peer-reviewed research (Haddaway et al., 2015), focusing exclusively on studies published in 2023 and 2024. This search resulted in a total of 776 records, comprising 771 from Scopus and five from WoS, which offer top publications from related disciplines such as Computer Science, Engineering, Social Science, Environmental Science, and were used for thematic exploration. Therefore, virtual reality technology on cycling safety education among primary school children has been gathered utilising the significant themes and search phrases that have been established (Figure 2).

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Step (3): A Suitable article has been selected for analysis. This scoping review established specific inclusion and exclusion criteria for the publications considered. Firstly, only those focusing on cycling safety were included. Secondly, only research articles qualified for inclusion, meaning conference papers, book chapters, conference reviews, and books were excluded from the list. Finally, only English-language papers published between 2023 and 2024 were considered (Figure 2).

Step (4): Projecting the data to be presented. Microsoft Excel will visually represent the data to enhance the thematic and comparative analysis. A detailed table will be provided to support the understanding of the findings and address the research questions, including the author's name, year of publication, studied variables, research implications, and central themes and sub-themes.

Step (5): Collating, summarising, and reporting the data. To effectively understand and present a comprehensive discussion on the impact of virtual reality technology on cycling safety education among primary school children, the findings were reorganised by topics, significant themes, and sub-themes. Each article is classified and analysed according to the themes and sub-themes from thematic and comparative analysis (Table 1). Figure 3 exemplifies the appearance of the published systematic literature.

Step (6): Discussion of the research findings. The outcomes were elaborated on in the paper's goals. Using virtual reality for cycling safety education is a new topic for many researchers. Therefore, the discussion on study limits and future research aims to enhance understanding of how virtual reality can educate primary school children about cycling safety. Following the last step is a conclusion.

3. Results and Findings

A total of 776 studies were identified through database searches using Scopus and Web of Science (WoS) with the search terms defined in the methodology. However, based on the inclusion criteria of empirical papers published in 2023 to 2024, and articles in the subject of cycling safety education with a social scientific status, 97 publications were eligible. Following the adjustment to account for duplicate papers (2 papers), only 56 papers could be used for this review. Of these 95 articles, further examination in the context of the objectives of this scoping review determined that 81 articles were different. Finally, only 14 articles were selected based on the reporting items indicated for thematic review as they were found to be more relevant and aligned with the research goals. The screening process is illustrated in Figure 2, following the PRISMA flow diagram (Moher et al., 2015).

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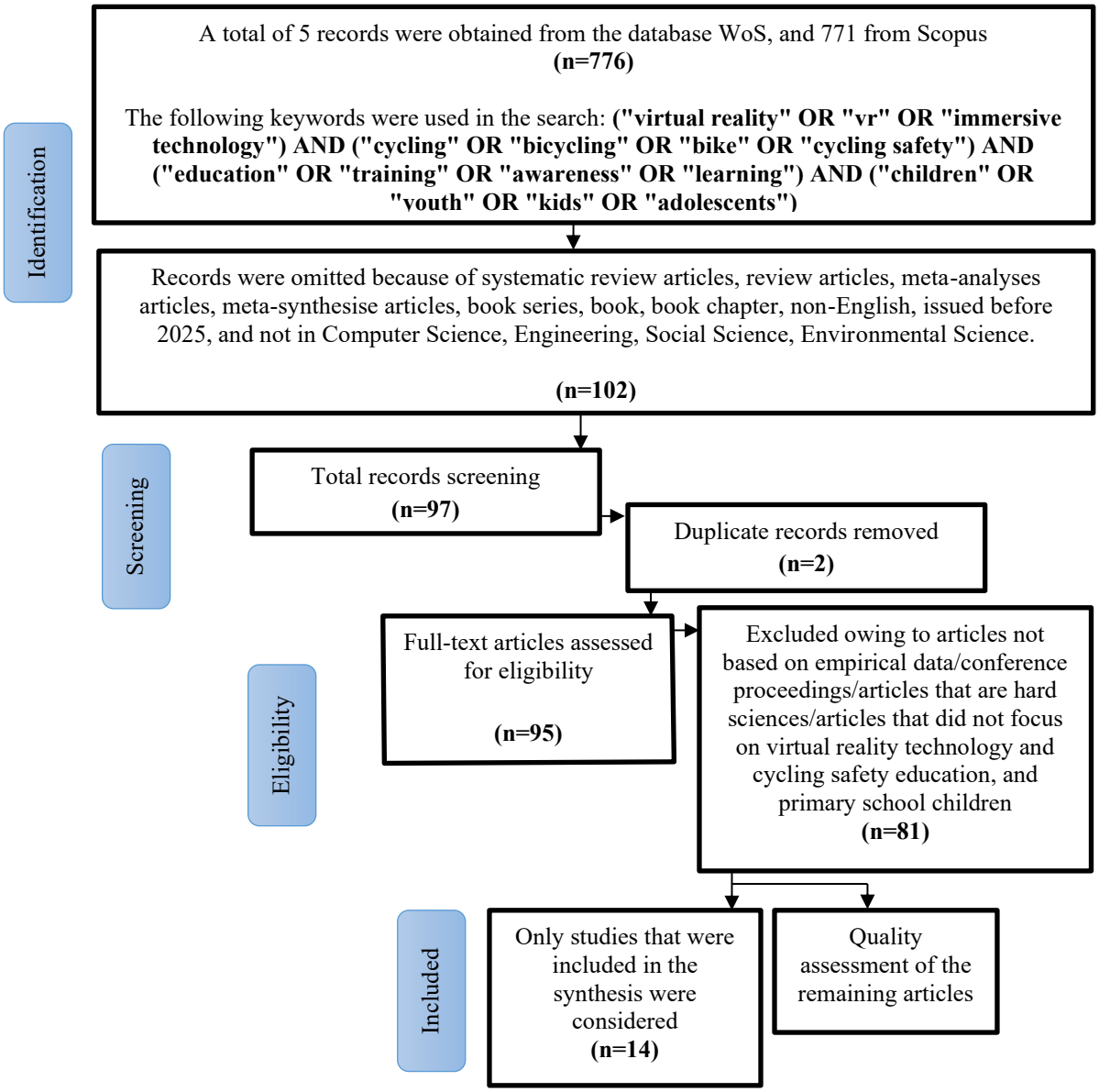

Figure 2. Flow diagram of research selection process using Preferred Reporting Items for Systematic Reviews (PRISMA) adapted from a study by Moher et al. (2015).

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Table 1. Charting the data.

Publication	Technology	Impact of virtual reality on cycling safety education	Sub-Theme(s)	Theme
You et al., 2024	Custom VR environment (EEG neurofeedback)	VR neurofeedback study; no direct cycling safety outcomes	Immersion	VR Engagement
Lange-Nawka et al., 2024	VR cycling exergame (competitive modes)	Motivation varied by gamer type; competitive and personalised VR modes increased user motivation	VR exergaming	
Seong & Hong, 2023	VR sports application	VR participation driven by social features highlighted the importance of online interaction and competition post-COVID	Social interaction	
Trifunović et al., 2023	Tablet vs paper test	Disadvantaged children were more engaged and scored higher using tablets than paper for traffic safety tests.	Digital learning	
Khademi et al., 2024	VR bicycle simulator	VR-based SEM found that informal surveillance (people's presence) increased women's perception of cycling security the most.	Built environment	Built Environment & Infrastructure
Beirens et al., 2024	Immersive VR cycling simulation	For vulnerable cyclists, VR identified key street safety features (bike paths, signage, calm traffic).	Street design	
Ramirez Juarez et al., 2023	VR (Maptionnaire) + eye-tracking	VR route-choice study showed that infrastructure quality strongly influences cyclists' route preference.	Streetscape design	
Schwebel et al., 2024	VR street-crossing simulation	Children crashed more in complex scenarios; boys and high sensation-seekers took more risks.	Child risk behaviour	Risk Behaviour
Torrens & Kim, 2024	Immersive VR (motion	Developed a VR system for crossing behaviour;	Crossing behaviour	

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Publication	Technology	Impact of virtual reality on cycling safety education	Sub-Theme(s)	Theme
	capture, agent models)	reproduced known effects and yielded high-resolution data on adult crossing scenarios		
Høeg et al., 2023	Social VR exergame (tandem bike)	VR tandem biking showed high usability and enjoyment; social collaboration motivated participants.	Rehabilitation and health	Health
Zhao et al., 2024	VR cycling with music using Head-mounted displays (HMD)	VR and music intervention led to significantly greater weight/BMI reduction and higher enjoyment than traditional cycling	Health and fitness	
Vuorio, 2024	Web-based VR learning environment	The VR safe-cycling environment was highly engaging for younger students (with some motion sickness reported)	Safety education	Safety Education
Zeuwts et al., 2023	Immersive VR bike simulator (HTC Vive)	VR hazard test showed valid performance: children fixated and braked for overt hazards, rating the simulator as realistic and fun.	Safety training	
Bishop et al., 2023	360° video VR Head-mounted displays (HMD)	Gamified VR improved children's looking behaviour and cycling confidence; explicit instruction accelerated learning.	Safety training	

Table 1 presents the 14 research publications included in the scoping review, selected according to the criteria outlined in Table 1 (Beirens et al., 2024; Bishop et al., 2023; Høeg et al., 2023; Khademi et al., 2024; Lange-Nawka et al., 2024; Ramirez Juarez et al., 2023; Schwebel et al., 2024; Seong & Hong, 2023; Torrens & Kim, 2024; Trifunović et al., 2023; Vuorio, 2024; You et al., 2024; Zeuwts et al., 202; Zhao et al., 2024). It describes the research and the mapping of themes and sub-themes. The analysis findings indicate that the positive application of virtual reality (VR) in cycling safety education among primary school children yields significant benefits, effectively addressing the research questions posed. These publications are categorised into five key themes based on their areas of focus: (1) VR Engagement, (2) Built Environment and Infrastructure, (3) Risk Behaviour, (4) Health, and (5) Safety Education. The

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scoping review develops themes and sub-themes to comprehensively address the second research question. The first theme is VR Engagement (Immersion, VR exergaming, social interaction, Digital learning), addressing learner motivation, engagement, and usability of VR.

The second theme is built environment and infrastructure (Built environment, street design, streetscape design), and VR was used to test how infrastructure and environmental cues influence perceived cycling safety. The third theme is risk behaviour (Child risk behaviour and crossing behaviour), which is focused on risk-taking and psychological influences on cycling behaviour. Health is the fourth theme (Rehabilitation and health, health and fitness) explored, and VR's role in promoting physical health is also explored. The last theme is Safety Education (Safety education and safety training), specifically examining VR applications to improve children's knowledge, hazard detection, and confidence in road safety.

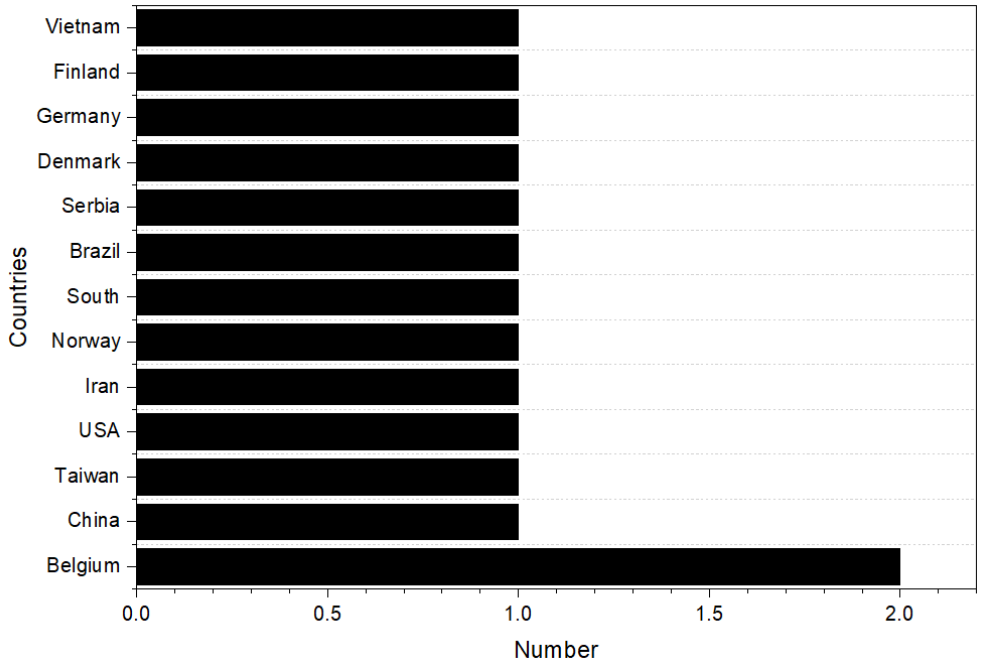

Figure 3. Number of research studies based on countries.

The study also covers a wide range of countries, as illustrated in Figure 3, which defines the research works included in this scoping study. Based on the data, these previous works have been conducted in 13 countries: Taiwan, Iran, Norway, South Korea, Brazil, the United States (US), Serbia, Denmark, Germany, Finland, China and Vietnam. In addition, two studies on the effects of virtual reality on cycling safety education have been conducted in Belgium. The findings of the analysis address the third research question by defining the nature of the published scientific literature. The research presented here shows that cycling safety education using virtual reality among primary school children has been studied in developed and developing countries. However, looking at the number of related works, the research can be considered relatively new and emerging in the context of primary school children. In other words, this approach is important. However, exploring this technology is still immature, and further research is needed to understand better the effects of the application of virtual reality

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technology for cycling safety education among primary school children. Another important point is that, compared to the general literature on cycling safety education, this volume is still considered limited in the context of primary school children. This suggests that future research on cycling safety education is welcome, and more technological aspects can be explored to develop a comprehensive understanding of the importance of cycling safety education using virtual reality in the context of primary school children.

4. Discussion

The thematic analysis highlights the broad potential of virtual reality (VR) as a tool in cycling safety education, not only in direct behavioural training but also in addressing psychological, environmental, and motivational dimensions. The theme of VR use finds that children are more motivated when learning is interactively tailored to their preferences (Lange-Nawka et al., 2024). For example, competitive elements and game modules can increase intrinsic motivation and focus. However, not all experiences are equally accessible. Trifunović et al. (2023) mention that digital modes are preferred among children with disabilities. Furthermore, a study by Vuorio (2024) noted issues such as dizziness among younger users, suggesting that VR interfaces must be carefully age-adjusted to ensure usability without discomfort. VR applications offer a new way to assess how specific infrastructure features affect perceived safety in the built environment and infrastructure. Results by Beirens et al. (2024) and Khademi et al. (2024) suggested that small design elements, such as greenery or signage, can influence whether children or vulnerable cyclists feel safe. Urban planners and policymakers can use VR feedback to prioritise infrastructure development based on real user responses rather than assumptions.

In health themes, VR must go beyond education by supporting physical well-being and emotional engagement. A study by Zhao et al. (2024) showed that VR use can improve focus when paired with music and gamification and has measurable effects on weight and enjoyment. Subsequently, Høeg et al. (2023) extended this idea to older adults to show that VR games can promote social interaction and motor activity. Opportunities for multi-generational VR cycling programs that promote safety, exercise and digital literacy can be suggested. Furthermore, cycling risk behaviour and traffic psychology require further exploration. Although VR helps identify behavioural traits such as risk-taking or poor route judgment (Schwebel et al., 2024; Bi et al., 2023), changing these behaviours remains challenging. The tendency of sensation-seeking children to ignore risks even in immersive environments suggests that VR devices alone cannot address all psychological variables. However, using VR as a diagnostic and experiential tool is valuable for researchers studying child safety and traffic psychology.

In summary, using an immersive VR device, cycling safety education increases situational awareness and develops confidence in primary school children (Zeuwts et al., 2023; Bishop et al., 2023). VR tools can simulate dangerous scenarios in a safe compound and facilitate children's experiential learning. The interactive nature of VR is also consistent with the principles of child-centred pedagogy, which has been shown to increase long-term knowledge retention (Pham et al., 2024).

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4.1 Limitations and Recommendations

While the 14 reviewed studies highlight promising virtual reality (VR) applications in cycling safety education, several limitations must be acknowledged. First, many studies were small-scale or pilot interventions, often using convenience samples of children or adult volunteers in controlled settings. As a result, findings may not be generalisable across broader populations or real-world cycling environments. Additionally, while many studies reported positive engagement and awareness outcomes, only a few, such as Pham et al. (2024) and Bishop et al. (2023), assessed long-term retention or real-world behavioural transfer. Furthermore, usability issues such as motion sickness were mentioned (Vuorio, 2024), indicating a need for careful design tailored to children's developmental stages.

To address these gaps, future research should focus on conducting longitudinal studies that assess immediate learning outcomes and long-term behaviour changes in real cycling contexts. Comparative studies between VR-based and traditional training methods could provide insights into cost-effectiveness and pedagogical efficiency. Researchers are encouraged to investigate how gender, socio-economic background, and digital literacy affect VR effectiveness. Finally, collaboration between educational institutions, city planners, and tech developers is essential to scale up VR cycling programs in schools and communities. These joint efforts can ensure that VR content is contextually relevant, affordable, and accessible.

4.2 Implications

This study elucidates that virtual reality (VR) can potentially transform cycling safety education, especially among primary school children. Its interactive nature aligns well with experiential learning principles and offers a safe, repeatable platform for developing hazard awareness and cycling confidence. VR can modernise safety programmes and engage students through gamified learning among educators or researchers. Urban planners can use VR tools to test infrastructure designs with honest user feedback. Healthcare professionals may adopt VR exergames to promote physical fitness alongside safety awareness. In short, integrating VR across education, planning, and health sectors could create safer, healthier, and more cycle-friendly communities.

5. Conclusion

There has been growing interest in virtual reality (VR) as an educational technology, especially regarding teaching cycling safety. This scoping research explores the existing body of evidence on VR-based cycling safety instruction for primary school learners. The two large electronic information databases were searched methodically in Scopus and Web of Science. This scoping review synthesised evidence from 14 studies exploring the use of virtual reality in cycling safety education for primary school children. Thematic analysis revealed five key areas: education, engagement, infrastructure, health, and risk psychology. Findings confirm that VR effectively increases engagement, enhances learning outcomes, and simulates real-world hazards. However, future research must focus on larger samples, behavioural follow-up, and inclusive design. With continued development and collaboration, VR promises to make cycling safer and more accessible for young learners across diverse contexts. In conclusion, recent

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studies show that VR-based cycling safety education has excellent potential to enhance safety outcomes among primary school children. However, more rigorous studies, primarily randomised controlled trials, are needed to support these studies and establish the best conditions to implement them.

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