

Research article

Effectiveness of digital media in accident prevention among adolescents—a comparison between VR- and tablet-based approaches

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Despite ongoing efforts, traffic accidents continue to pose a significant risk to children and adolescents. Conventional traffic education often fails to account for age-specific developmental stages or to engage pupils in an age-appropriate and engaging way. This study examines the integration of a Virtual-Reality (VR) module into an existing digital accident prevention programme within the EU Horizon project SOTERIA and evaluates whether this immersive extension is associated with improved pupils' understanding of accident causes and enhance their safety awareness. The programme was implemented in two research settings in Germany: in the City of Munich, the conventional tablet-based programme was conducted, while in Saxony the programme was extended with a VR module to allow experiential exploration of real accident scenarios. Standardized questionnaires assessed pupils' satisfaction, perceived learning, usability of the VR technology, and changes in attitudes and safety-related behaviour. The results suggest that pupils in the VR-supported programme reported higher engagement, a deeper understanding of traffic risks, and more positive safety-related attitudes and behaviours than those participating in the tablet-based programme. These findings highlight the potential of immersive digital media to support road safety education through experiential learning and suggest that VR may be a valuable addition to established prevention programmes.

1. Background

The World Health Organization asserts that road traffic accidents represent the leading cause of mortality among children and young adults aged between five and twenty-nine years, with approximately 1.19 million fatalities globally each year (WHO, 2023). Children are particularly vulnerable as pedestrians and cyclists due to their developmental limitations in hazard perception, attention regulation and speed estimation (Barton & D., 2007; Schwebel et al., 2012). The transition from supervised to independent mobility during adolescence – typically between 10 and 15 years of age –

creates a period of elevated risk exposure observed across high-income countries (ITF, 2025).

Within the European Union, considerable progress has been made in reducing child road traffic fatalities over the past decades. However, children and adolescents remain disproportionately represented among vulnerable road users, particularly as pedestrians and cyclists (Carson & Jost, 2025; European Commission, 2025). Countries such as the Netherlands, Sweden and the United Kingdom have implemented comprehensive road safety education programmes as part of national strategies,

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yet evaluations consistently highlight the challenge of engaging adolescents effectively (Dragutinovic, 2006; Twisk et al., 2014). The situation in Germany illustrates these broader European patterns and serves as a case study for examining innovative approaches to road safety education.

Despite preventive measures, traffic accidents continue to pose a significant risk to children and young people in Germany. The increasing complexity of road traffic, rising traffic volumes and distractions caused by smartphones are increasing the danger (BASt, 2024). The so-called ‘parent taxis’ often result in pupils participating less independently in traffic, which limits their development of a safe and independent traffic behaviour and at the same time has negative environmental impacts (ADAC-Stiftung, 2024).

In 2024, a total of 27,261 children were involved in accidents on German roads (+2.9% compared to 2023), of whom 44 died (Destatis, 2025). On average, one child (up to 15 years of age) was injured in road traffic every 19 minutes in Germany (Destatis, 2025). Within accidents involving children and young people in urban areas, especially cycling and walking play a major role (see Figure 1).

The data shows that 10- to 15-year-olds are most frequently involved in bicycle accidents in urban areas (Destatis, 2025). While the proportion of children and young people involved in car accidents decreases with age, the proportion of children and young people involved in bicycle accidents increases until the age of 15. From this age onwards, longer commuting distances to school and the transition from travelling by bus to using mopeds – classified within the category “other” – lead to a higher involvement of young people in accidents with motorised vehicles (see Figure 1).

The way to school accounts for a large proportion of the regular daily journeys made by this age group (Bundesverkehrsministerium, 2025). The mobility behaviour of children and young people aged 10 to 15 (transition from primary to secondary school in Germany)

changes significantly in this regard. Recent studies have indicated that they allocate more time to travel independently, covering longer distances with greater frequency for leisure and educational purposes (Bundesverkehrsministerium, 2025). Despite the fact that young people in this age range are increasingly undertaking more complex mobility tasks, the educational system offers only limited structured support. As illustrated in Figure 1, there is a high prevalence of child road traffic injuries, which may result in the necessity for enhanced road safety and mobility education in schools, particularly for this vulnerable age group.

As Funk demonstrates, the provision of mobility education in Germany varies considerably across federal states (Funk, 2023). Indeed, the majority of such education is primarily designed for preschool and primary school pupils. As a result, basic training in safe traffic behaviour is mainly provided until around twelve years of age, while only a limited number of prevention programmes specifically address adolescents between twelve and sixteen years of age. One such programme is the road safety education programme offered by DEKRA, which is designed for children up to the age of twelve. The programme was conceived with the intention of providing knowledge and materials on traffic safety in schools to pupils in both older primary and younger secondary school (DEKRA, 2025). In practice, a noticeable gap exists in the continuous provision of road safety education for adolescents, leading to a deficit in age-appropriate and motivating materials. Furthermore, an analysis of available road safety materials for cyclists and pedestrians reveals a marked disparity between the resources allocated and the number of accidents involving these groups. Moreover, conventional road safety education often fails to engage this group adequately in the context of their digitally shaped everyday lives. Consequently, there is a need to promote their road safety competencies in a target group-specific manner and to raise their risk awareness within road traffic (Funk, 2023).

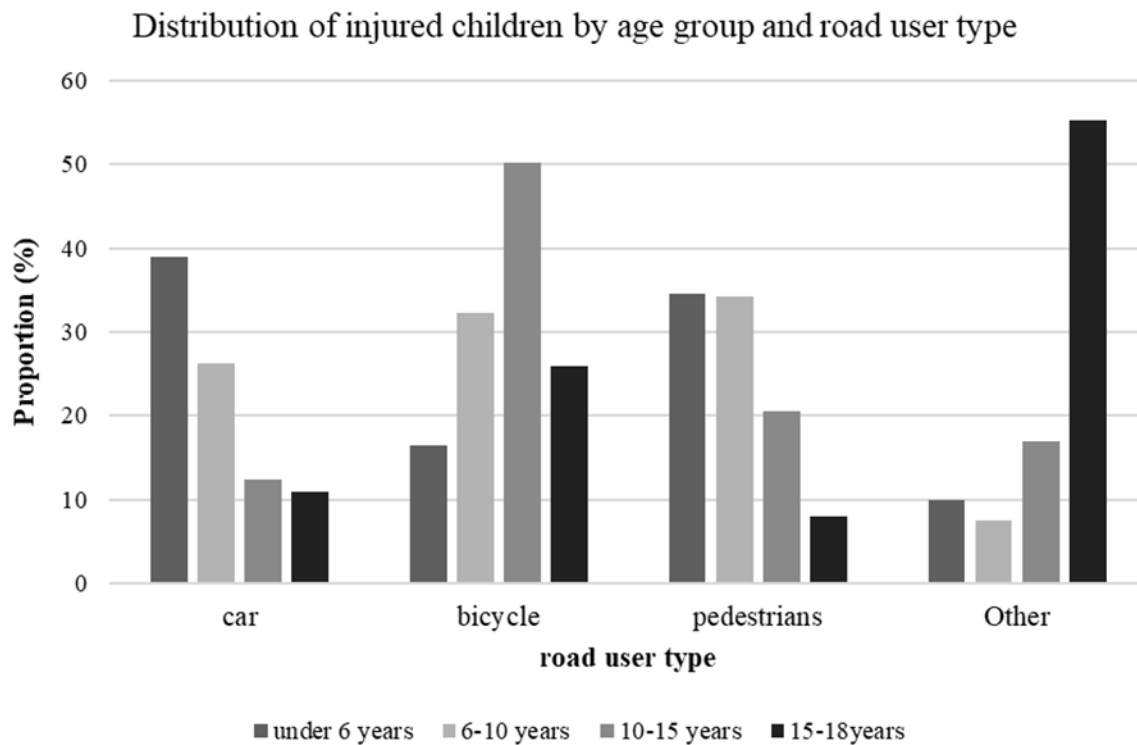


Figure 1. Children involved in road traffic accidents by age group and type of road user in urban areas (Destatis, 2025), own illustration

This is of relevance in the context of the developmental psychological prerequisites for safe traffic behaviour. Despite the increasing demands on their mobility, adolescents do not yet possess fully developed perceptual and decision-making competencies (Schlag *et al.*, 2018). Even among 10- to 12-year-olds, difficulties in estimating time to arrival (TTA) persist, with a systematic tendency toward underestimation (Hoffmann & Payne, 1980). Biological and hormonal changes during adolescence further increase sensitivity to social approval and promote exploratory and reward-seeking behaviour (Feenstra & Ruiter, 2010). Although adolescents are capable of rational decision-making, immediate social benefits often outweigh long-term consequences, fostering rule-deviant behaviour and heightened risk-taking aligned with peer norms (Wang *et al.*, 2019). Research findings indicate that the fundamental issue resides less in distorted risk perception and more in the deliberate choice to engage in high-risk behaviours. Adolescents do not perceive themselves as invulnerable; from around the age of 14 years, their risk

perception is comparable to that of adults (Feenstra & Ruiter, 2010). This suggests that behavioural choice is a pivotal factor in determining safety behaviours. Adolescents who perceive a situation as safe – such as crossing a street at an undesignated location – are less likely to engage in safe behaviours like waiting for a traffic signal (Poudel-Tandukar *et al.*, 2007). Additionally, risk sensitivity is also shaped by personality traits, peer influence, and attitudes toward traffic rules (Zhao *et al.*, 2020).

In recent years, virtual reality has emerged as a promising educational technology, offering immersive learning environments that enable experiential and situated learning experiences not achievable through traditional media (Merchant *et al.*, 2014; Radianti *et al.*, 2020). Meta-analyses have demonstrated that VR-based instruction can improve learning outcomes compared to conventional methods, particularly when tasks benefit from spatial understanding, perspective-taking or emotional engagement (Merchant *et al.*, 2014). The sense of presence – the subjective feeling of “being there” –

has been identified as a key mechanism through which VR facilitates deeper cognitive understanding (Makransky & Terkildsen, 2019). This sense of presence is not a single phenomenon but rather a combination of representational, participatory, and affective immersion that captures learners' attention and engagement (Jackson, 2024). By simulating realistic environments, VR can enhance pupils' motivation and support the comprehension of complex concepts through direct visualization and interaction (Paramita et al., 2024).

The creation of such immersive experiences relies on the synchronization of several key technical components (Đorđević et al., 2024):

- **Visual and auditory systems:** Head mounted displays (HMDs) block external stimuli and fill the user's field of view with a stereoscopic 3D environment, often complemented by spatial audio.
- **Interactivity:** Handheld controllers, sensors, and hand tracking technologies enable learners to manipulate virtual objects and navigate the environment in a natural manner (Singh-Pillay, 2024).
- **Sensors and computational processing:** These systems ensure that the virtual environment responds to user movements in real time, which is essential for maintaining the illusion of presence.

This technological integration transforms learners from passive observers – as in traditional desktop or video-based instruction – into active participants at the centre of the experience (Huang et al., 2025). Empirical studies indicate that this heightened level of interaction and presence in VR can lead to increased engagement and motivation compared to conventional learning methods (Alrehaili & Al Osman, 2022; Bandi et al., 2024).

Within road safety education specifically, VR has been employed to train children and adolescents in pedestrian and cycling skills. Schwebel and colleagues conducted

a series of studies demonstrating that VR-based pedestrian training improved children's street-crossing behaviour, hazard perception and gap selection in both virtual and real-world settings (Schwebel et al., 2012; Schwebel & Gaines, 2008; Schwebel & McClure, 2014). Similarly, Morrongiello et al. found that children trained in a VR environment showed improved evasive action skills when confronted with unexpected traffic hazards (Morrongiello et al., 2015). Bart et al. compared street-crossing performance in real and virtual environments, providing evidence for the ecological validity of VR as a training tool for young road users (Bart et al., 2008). These studies suggest that VR enables safe exposure to dangerous traffic scenarios that would be unethical or impractical to recreate in real-world training contexts.

Research comparing VR with other digital media has yielded nuanced findings. Makransky et al. found that while VR increased the sense of presence and engagement, it did not always lead to superior learning outcomes compared to desktop-based simulations, suggesting that instructional design plays a critical role in leveraging the potential of virtual reality (Makransky & Terkildsen, 2019). Meyer et al. demonstrated that pre-training strategies could enhance learning effectiveness in VR compared to video-based instruction (Meyer & Omdahl, 2019). Virtual Reality offers a powerful pedagogical countermeasure by addressing these specific characteristics within a controlled environment. It is particularly effective in targeting contemporary risk factors that are difficult to replicate in traditional training settings. For example, VR simulations can directly expose adolescents to the dangers associated with distraction from mobile phones and headphones, thereby raising awareness of a key behavioural risk identified in recent studies (Nawaz et al., 2025). However, direct comparisons between VR- and tablet-based approaches within the same educational programme remain scarce, particularly in the context of adolescent road safety education. This study addresses this gap by comparing a tablet-based accident

reconstruction module with an extended VR-based version within an established prevention programme, thereby providing empirical evidence on the differential effects of these digital modalities on engagement, understanding and behavioural intentions.

2. Aim

The objective of the evaluation within the SOTERIA project was to ascertain the added value of the VR module within the accident prevention programme in comparison to the existing tablet-based training. The initial focus of the programme was placed on the shifts in perception and acceptance among the participants. Furthermore, the usability of VR was evaluated with a particular focus on the pupils' ability to operate the VR glasses independently and to comprehend the accident situations shown. In addition, changes in the awareness and anticipation of specific traffic risks – especially dangers for pedestrians and cyclists – were evaluated, as was their lasting impact on participants.

3. Method

3.1 Description of FAPS + VR

The Fraunhofer IVI Accident Prevention School (FAPS) was developed to close the existing knowledge gap in road safety education for young people aged 13 to 15 (Erbsmehl & Pohle, 2019). The aim of the training is to sensitise pupils to critical traffic situations, raise their awareness of accident risks and promote their ability to act in a proactive, safe and anticipatory manner in road traffic. The training also teaches pupils that even correct behaviour on their part cannot always prevent accidents. It is important to note that accidents can still occur as a result of the misconduct of other road users. Moreover, the FAPS programme encourages young people to engage with real traffic situations, thereby enabling them to transfer the skills they have acquired to everyday life.

The training is based on a modular structure that combines sequential learning steps: The

introductory modules 0 and 1 aim to raise awareness by encouraging pupils to report on their own experiences, identify critical points on their own way to school and assess the frequency of accidents in their school surroundings. In modules 2 and 3, real accident statistics are evaluated and accident hotspots in the school area are analysed with the help of anonymised police recorded accident reports. In module 4, participants use software to reconstruct traffic accidents statically on tablets. In this process, they analyse the causes of accidents, consider the perspectives of all involved accident parties and examine visibility conditions such as viewing angles, view obstacles and blind spots. The change of perspective enables them to understand critical situations realistically and derive alternative strategies for safe behaviour in road traffic.

Before the start of the SOTERIA Horizon Europe project first virtual reality scenarios were available. The aim within the SOTERIA project was to develop an educational concept based on these scenarios that would enable the integration of a VR module (module 5) into the existing training programme. Module 5 expands on the existing training programme with the use of VR technology and deepens the knowledge gained in module 4 through a fully immersive learning experience. Based on official accident statistics and detailed accident analyses, particularly serious and frequently occurring accident scenarios involving pedestrians and cyclists were identified and reconstructed as real accidents in a dynamic 3D environment. Figure 2 shows sample screenshots of the VR module.

In contrast to the tablet-based reconstruction in module 4, pupils experience the accident situations from a first-person perspective of all involved parties in real time. Obstructed views, angles of vision and blind spots become physically and emotionally tangible, as learners actively move around in the virtual space and can take on the perspectives. This leads to a particularly intense understanding of the causes of accidents, risky behaviour and the potentially fatal consequences of critical traffic situations.



Figure 2. Example screenshots of accident situations displayed in the VR module, where a cyclist appears from a tree-lined avenue, a pedestrian appears in-between parked cars and a cyclist moves through the blind spot of a turning truck (from left to right)

The study was carried out using a control group design. In Munich, the training was conducted in its previous form up to module 4, while in Saxony, the new educational concept, including the VR module (module 5), was implemented. This structure not only enabled age-appropriate teaching of road safety skills but also allows a direct comparability between the conventional tablet-based training and the extended VR-based method. Both variants were evaluated as part of the SOTERIA project to investigate the effect of the immersive learning environment on the safety awareness and anticipatory behaviour of young people.

The VR module was developed using the Unreal Engine, where all accident scenarios were modelled, animated, and rendered as 360° immersive video sequences. These scenes are delivered through a WebXR-based 360° web application (“JARVIS 360 WebXR Player”), which runs directly in the integrated browser of standalone VR headsets. As the system is based on standard WebXR technology, it is hardware-independent and can be used across different VR devices without architectural changes. Originally tested on Oculus Quest headsets, the application is now operated on Pico VR devices.

3.2 Evaluation design and implementation

Immediately after completing the training at their respective schools, the participating pupils received standardised questionnaires. The questionnaires used in the city of Munich and in Saxony contained an identical core set of questions, which allowed a direct comparison of perception, acceptance and learning effectiveness between the tablet-

based and VR-based training. Additionally, the questionnaire administered in Saxony incorporated specific questions concerning the VR module, with the objective of capturing the participants’ experiences with immersive technology and its impact on their safety awareness. As the evaluation followed a post-test-only design and no pre-test measurements were conducted, changes in knowledge, attitudes, or safety awareness could not be assessed directly.

3.3 Questionnaire and data collection

The common questions in both questionnaires consisted of different sections focussing on the perception of the learning method, for example whether it was perceived as varied and appealing, as well as on the participants’ willingness to recommend the prevention programme to others. In addition, the questionnaire included a section on the contents and aspects of the training that were particularly memorable, and which allowed for the drawing of conclusions regarding the respondents’ own safety behaviour and their attitude towards road safety. Moreover, the questionnaire was designed to undertake a comprehensive evaluation of the programme, addressing both perceived strengths and weaknesses, and proposals for enhancement.

The specific questionnaire section on the VR component focused on the independent use of VR glasses and software, the comprehensibility of the virtual representations, the support in understanding the risks of motorised traffic for pedestrians and cyclists and the appropriateness of the duration of VR use.

Contextual information was also collected to identify possible influencing factors, including the location of the school (urban or rural) and the type of secondary school (grammar or high school). This enabled an investigation of the extent to which school conditions may influence the perception, acceptance and impact of the training variants.

3.4 Questionnaire design

The questionnaire was developed based on established evaluation criteria commonly used in educational media assessment. To ensure content validity, methodological approaches from schoolbook research were considered, including the Bielefelder Raster (Laubig & Peters, 1986), the Wiener Raster (Bamberger, 1998), and more recent tools like the Levanto Tool (Wirthensohn, 2012), which include criteria such as relevance, comprehensibility, didactic quality, effectiveness, transferability, and user appropriateness. These frameworks provided a meta-level rationale for selecting question types and evaluating dimensions such as usability, perceived learning outcomes, acceptance and behavioural relevance.

Furthermore, concepts from project evaluation – particularly relevance, effectiveness, efficiency, and process evaluation – were incorporated to justify the inclusion of items related to learning impact, perceived behavioural change, and situational awareness. This methodological foundation ensured that our questionnaire captures both descriptive and evaluative aspects relevant to road safety education.

All questionnaire items used a 4-point Likert scale without a neutral midpoint (“agree”, “rather agree”, “rather disagree”, “disagree”). For some items, an additional “not applicable” option was provided. The format was chosen to encourage clear directional responses and follows common practice in educational media evaluation.

The questionnaire was provided in printed form and filled out by the pupils directly after the accident prevention session during

regular class time. As the questionnaire was administered on paper, no digital platform or software tool was involved.

3.5 Participants

A total of 247 participants were invited to complete the questionnaire as part of the study. Of the 93 participants from the city of Munich, 27 (29.03%) were from grammar schools (“Gymnasium”) in municipal areas, and 66 (70.97%) were from high schools (“Oberschule”) in rural areas. In comparison, in the Saxon accident prevention school, 110 of the 154 participants who utilised the VR module were enrolled from urban grammar schools (71.43%), while 44 participants (28.57%) were recruited from rural ones. To evaluate the effectiveness of digital media in accident prevention, a comparison was carried out between the tablet-based results in Munich and the extended VR approach within Saxony.

3.6 Data analysis

The data analysis consisted of a simple Chi-Square test as method to determine if there was a significant variation in responses between the two test groups. Should a Chi-Square value be higher than the specified significance level, it can be deduced that the observed data varies significantly from the expected data. The significance level was determined to be $\alpha=0.05$, which corresponds to a probability of 5%. If the calculated p-value exceeds the significance level ($p>\alpha$), it can be deduced that the result is not significant, and the null hypothesis is upheld. This finding indicates that VR users in Saxony attain equivalent learning outcomes to pupils in Munich who do not participate in the VR module. The software utilised for this purpose was MS Excel. The following analysis will examine the specific results of the VR module.

4. Results

4.1 Comparison of tablet-based and VR-based programme

The ensuing figures offer a comprehensive evaluation of the specific components of the accident prevention school, accompanied by a meticulous comparison of the outcomes from the city of Munich and the federal state Saxony. The findings demonstrated a high level of consistency between both regions, with pupils expressing a generally positive approval of the course, irrespective of the additional VR module. The initial aspect requested and analysed pertained to the overall satisfaction levels of the course, both between the two locations and two types of schools. The difference is evident when analysing the participants' satisfaction with the learning methodology employed in the accident prevention programme (see Figure 3). In the city of Munich, as illustrated on the left side of the diagram, with 77.78% of respondents enrolled in urban grammar schools and 81.82% in rural high schools, the proportion of respondents who rate the course as 'good' or 'rather good' is almost equal. However, a discrepancy was observed in the ratings given by respondents attending school in rural and urban areas. In Munich, where the course was found to be more favourably evaluated in rural schools, 30.30% of individuals attending school in rural areas evaluated the subject as "good", while this figure was halved, at 14.81%, among their urban counterparts ($p=0.654$). This outcome was expected due to the absence of statistical significance ($p > \alpha$). This phenomenon stands in contrast to the situation in Saxony, where the proportion of respondents who expressed a 'good' rating was notably higher in urban areas (70.91%) compared to rural areas (40.91%). In this case, the difference was found to be significant ($p \leq \alpha$ with $p=0.035$).

In the following the data from Munich, excluding the VR module, is compared with the data from Saxony, including the VR module, regarding the impact of the accident prevention schooling. The questionnaire's key findings indicate that the VR module

significantly increased the pupils' satisfaction with the programme, as illustrated on the left side in Figure 4. In Munich, 36.56% of pupils provided a positive evaluation of the accident prevention school, with an additional 35.48% rating it as "rather good". In contrast, the general rating in Saxony is higher, with 93% of Saxon pupils expressing satisfaction following the completion of the VR module. The implementation of VR has been developed to enhance the programme's appeal among pupils. This is evidenced by the outcomes of the evaluation in terms of the pupils' recommendations of the course, as presented in Figure 4 on the right. In the city of Munich, 53.76% of respondents stated that they would or rather would recommend the accident prevention school to a friend. In contrast, participants in Saxony reported a significantly higher level of recommendation in the study, with more than 80% of respondents ($p \leq 0.05$).

These are key positive aspects, as is the memorability of the course, which is also beneficial for the VR module, as illustrated on the left in Figure 5. The questionnaire administered in Munich further revealed that 16.13% of respondents expressed the opinion that the employed pedagogical approach would leave a lasting impression. The outcomes of the questionnaire in Saxony revealed that this figure was almost double, with 30.52% of participants holding the same view ($p \leq 0.05$). The project work had a significantly varying degree of influence on the attitudes towards road safety behaviour of participants in Munich and Saxony. The study revealed that in the absence of the VR module in Munich, only 12.90% of participants exhibited a change in attitude, as demonstrated in Figure 5 on the right. In Saxony, where the accident prevention school was employed with VR, this figure increased to 31.82% ($p \leq 0.05$).

The following question is presented in summary form, without the inclusion of explicit numerical data or graphical representations. The feedback received identifies the VR module as a contributing factor to the establishment of a more sustainable awareness of road safety. Next

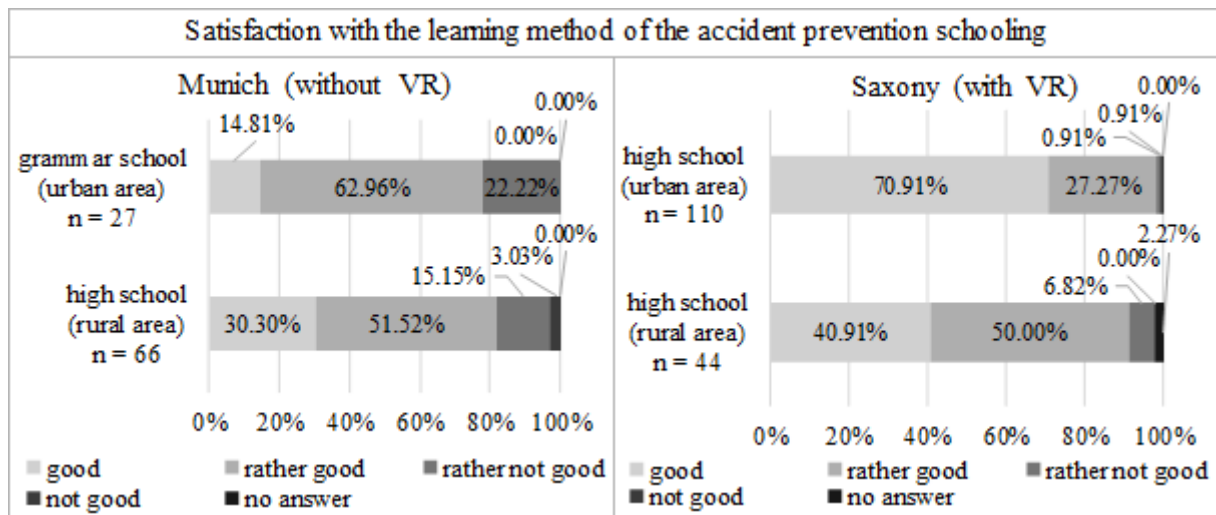


Figure 3. Pupils' perceptions of the learning methodologies employed in the accident prevention programme on the left in Munich (without VR) and on the right in Saxony (with VR module)

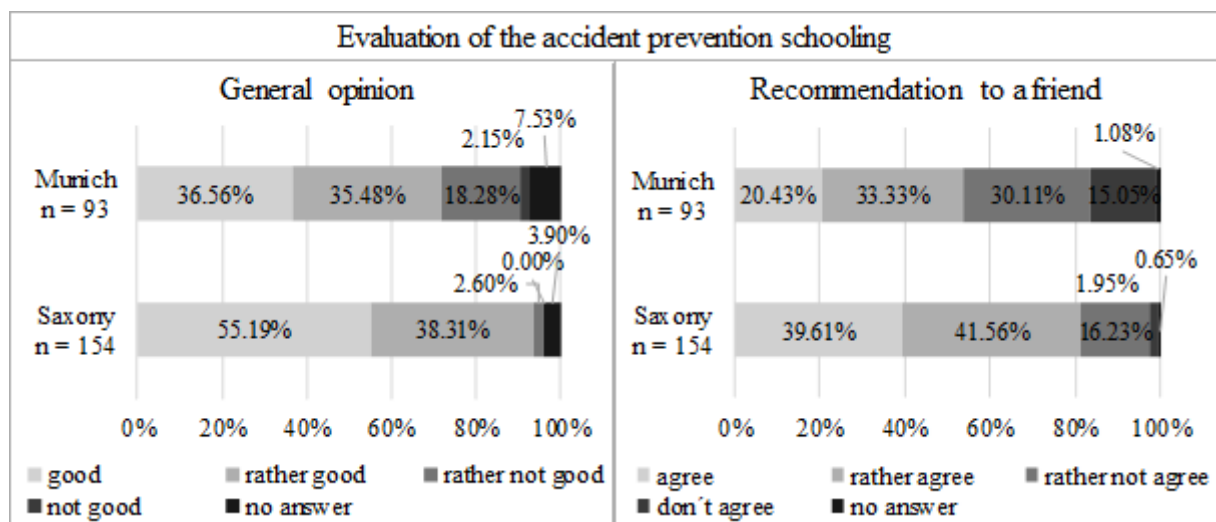


Figure 4. Opinion of pupils on the accident prevention schooling in Munich (without VR) and in Saxony (with VR) on the left and recommendation of the course to a friend of Munich and Saxon pupils on the right side

to a higher rate of recommendation, a greater proportion of respondents (>75%) stated agreement and rather agreement that more attention will be paid to safe road behaviour from Saxon participants than from Munich ones, both in terms of the behaviour of one's own and other road users. While approximately 33% of respondents in both regions expressed a certain degree of agreement, only 18% of Munich pupils indicated full willingness to dedicate more attention to the issue of road safety. This figure is more than half lower than the percentage

of respondents in Saxony who expressed a similar degree of agreement.

4.2 Contribution of VR module

As previously mentioned, the initial questionnaire themes of this segment are also evidenced solely by quantitative data. It is important to note that the participants from Saxony highlighted the significant impact of the VR module on the aforementioned changes in attitudes towards road safety. This is in accordance with the contribution of the VR module to attitude change in

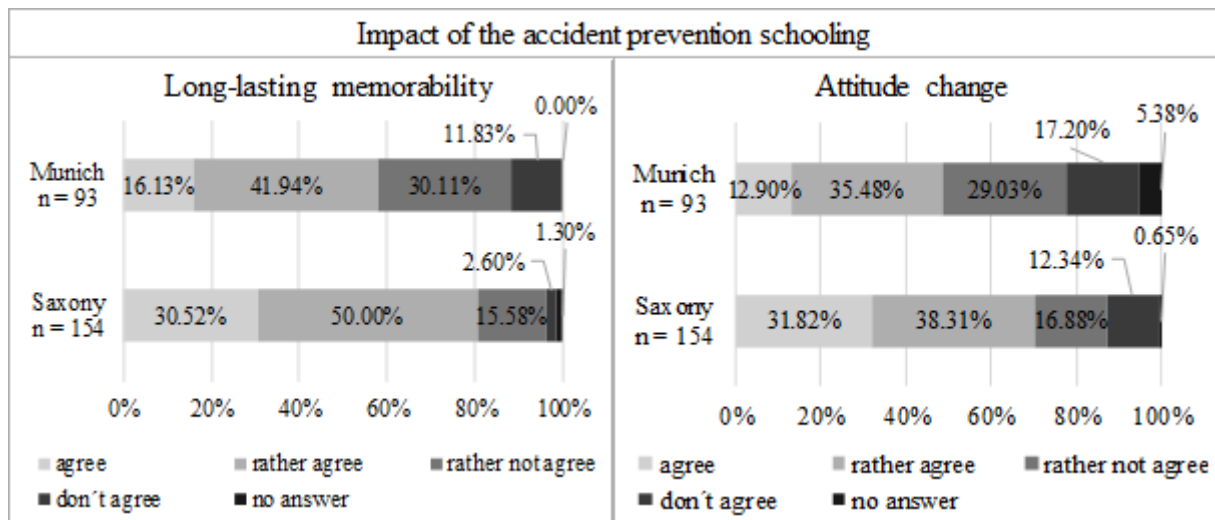


Figure 5. Memorability of the learning process in accident prevention school on the left and effectiveness of the programme in terms of promoting attitude change regarding road safety on the right, both in Munich and Saxony

road safety behaviour. The results of the questionnaire section, which was exclusively concerned with the VR module, indicated that approximately half of the pupils (45.45%) participating in Saxony attested to the VR module having a role in modifying their attitudes, with an additional 28% expressing a rather positive contribution. The VR application's design was intuitively structured, enabling pupils to engage with the VR module autonomously. This finding was further substantiated by the responses to the administered questionnaire, with over 70% of respondents expressing complete approval and only a small percentage rejecting or partially rejecting the application. The consensus among most test subjects was that the VR application contributed to an enhanced comprehension of traffic and hazardous situations.

The question of whether new insights into the visibility of pedestrians and cyclists were gained, and whether the VR application provided significant support in this regard, can be answered by examining Figure 6. As illustrated on the left-hand side, 53.25% of Saxon participants obtained novel insights into the visibility, with a further 25.97% stating they rather did. Additionally, 38.96% of pupils reported that VR use had been beneficial, with an additional 38.96% stating that it had rather

enhanced their perception of pedestrians and cyclists (see right-hand side).

The fact that most participants indicated a desire for additional time for the VR module during the accident prevention schooling also serves to emphasise the favourable opinion of the implementation of the VR module in accident prevention training, irrespective of region or school level.

5. Discussion

This finding emphasises the important role of the VR module in raising awareness of road traffic risks, while also highlighting the limited time available for this approach to safety education. Overall, both formats received positive feedback across all questionnaire items. The increase in satisfaction and engagement associated with the VR module in Saxony is consistent with previous research on immersive learning (Bandi *et al.*, 2024; Paramita *et al.*, 2024; Radianti *et al.*, 2020). Engagement of learners is imperative for the successful transfer of knowledge. The immersive nature of VR has likely contributed to greater attention and emotional engagement, which in turn facilitated better retention of safety-related information, as indicated by the higher recommendation rates and improved recall in Saxony.

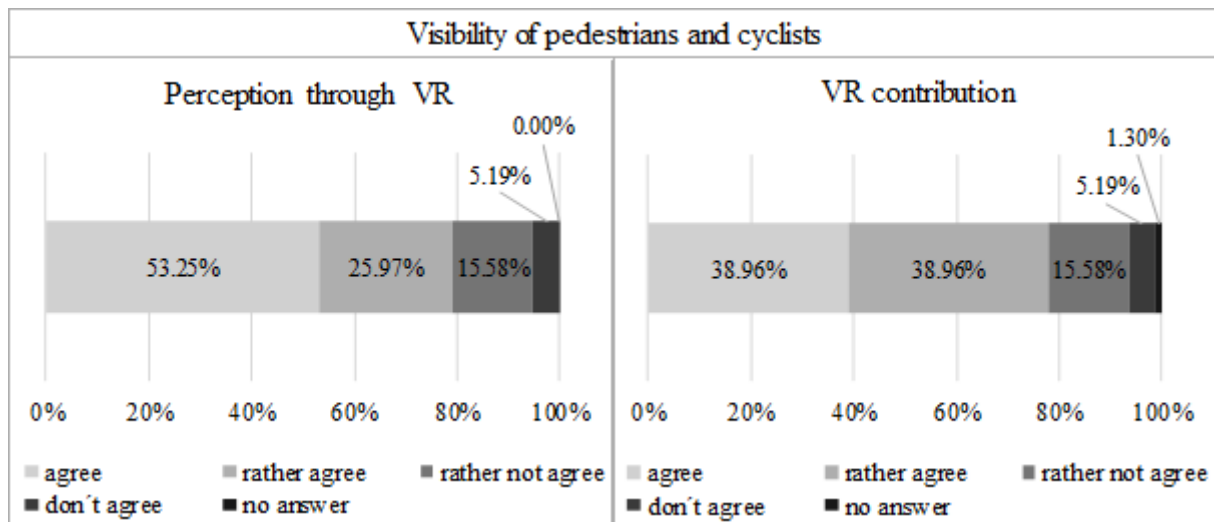


Figure 6. Experience of new findings on the visibility of pedestrians and cyclists within the accident prevention schooling on the left side and considerable assistance of VR in this regard on the right side; $p \leq 0.05$

The proportion of pupils who found the learning experience memorable increased almost doubled with the introduction of VR. This finding lends support to theories of deeper cognitive processing and memory encoding through multisensory and experiential learning environments using VR (Alrehaili & Al Osman, 2022). Moreover, the results of the study demonstrate a consistent improvement in awareness of traffic situations and the visibility of pedestrians and cyclists. This finding aligns with the results of previous studies on VR-based safety education, which emphasise the effectiveness of simulated environments for risk perception and hazard recognition (Dragutinovic, 2006; Huang et al., 2025; Merchant et al., 2014). The result that more than half of the participants reported gaining new insights into visibility conditions supports the notion that VR can effectively bridge the gap between theoretical knowledge and practical application. This is the sole means by which young people, who are not yet permitted to drive a vehicle due to not holding a driving licence, can gain an understanding of visibility from vehicles such as cars and lorries. This fact indicates that VR not only enhances enjoyment but can also be helpful in achieving meaningful learning outcomes, especially in areas requiring behavioural

awareness and risk perception (Meyer & Omdahl, 2019; Poudel-Tandukar et al., 2007; Zhao et al., 2020).

The extent of the observed change in attitude is contingent upon exposure time, intervention intensity, and contextual factors such as prior knowledge and the local traffic environment. The hypothesis is that variations in the students' initial experiences with traffic, infrastructure and digital technologies may influence their benefit from the programme. Despite the evidence from numerous studies that digital learning tools have consistent effects across different contexts, the present findings suggest that local conditions and school environments can influence how educational interventions are perceived and evaluated (Nawaz et al., 2025; Twisk et al., 2014). This discrepancy may be attributed to variations in the assumptions concerning the aforementioned factors, a subject that is seldom addressed in the extant literature.

The limitations outlined below confirm that a 'one-size-fits-all' approach may not be optimal and that educational interventions should be adapted to local conditions.

5.1 Limitations and recommendations for future research

It is crucial to acknowledge the limitations of the study. Firstly, the comparison between Munich and Saxony is not based on a controlled experimental design. Rather, it is based on two distinct regional implementations. Consequently, any observed differences in outcomes cannot be attributed solely to the presence of the VR module. Other contextual variables, such as teaching quality, school type and location, and socio-demographic factors, may also have influenced the results. These are just some of the possible influencing factors. Even the educational system differs from state to state in Germany.

Moreover, the study predominantly relies on self-reported data, which is subject to potential biases, such as social desirability or recall bias. In addition, the evaluation followed a post-test-only design, as no pre-test measurements were conducted. Therefore, changes in knowledge, attitudes, or safety awareness cannot be assessed directly. While subjective perceptions are important indicators of programme acceptance, they do not necessarily reflect actual behavioural changes in real traffic situations.

Attitudinal change and memorability were only measured in the short term, immediately after programme participation. The long-term effects, which are relevant to accident prevention, were not examined. Furthermore, participants expressed a desire for more time, suggesting that the duration of exposure to the VR module was limited. This may have limited the intervention's potential impact, which partly explains the moderate levels of reported attitude change.

These limitations highlight several avenues for future research. Future studies should employ more rigorous experimental designs, including pre- and post-test measurements and, where feasible, control groups, to better isolate the specific effects of VR-based interventions and reduce potential confounding factors. Further research would

contribute to more robust conclusions and help to assess the durability of learning outcomes and behavioural changes over time. It would be particularly valuable to investigate whether the observed improvements in awareness and attitudes towards safer behaviour translate into safer behaviour in real-world traffic environments.

Given the disparities observed between regions and school types, future research should also examine the influence of contextual factors more systematically. These include local traffic conditions, differences between urban and rural environments, school characteristics, and the role of environmental and socio-cultural variables in shaping the effectiveness of VR-based education. Such research would contribute to the development of more tailored and equitable interventions.

5.2 Policy implications for practice and education

The findings of this study have several implications for educational policy and practice. The evident advantages of VR suggest that the incorporation of immersive technologies into accident prevention programmes has the potential to significantly enhance their effectiveness and acceptance among pupils. Consequently, policymakers should consider the implementation of VR modules on a broader scale within school courses.

In view of the disparities observed between regions and school types, it is imperative to ensure that such innovations are implemented in a manner adapted to the specific characteristics of the school environment. This may require the adaptation of content to suit local traffic conditions, including the differentiation between urban and rural areas. Additional support should be provided for schools with limited technological infrastructure.

The favourable reception of the VR module, coupled with the expressed desire for increased usage, indicates a strong

willingness among pupils to engage with digital learning tools. It is imperative to invest in teacher training and technical resources if the full potential of these technologies is to be realised. Further investigation into the optimal exposure duration and instructional design within VR environments is recommended to maximise learning outcomes. Despite its potential, it is important to note that virtual reality should not be considered a replacement for conventional teaching methods, but rather a valuable supplement that can improve experiential learning and risk awareness (Makransky & Terkildsen, 2019). It has been identified that a combination of theoretical instruction and immersive simulation is a potentially beneficial approach to promote sustainable behavioural change in the context of road safety (Merchant *et al.*, 2014). Studies within educational psychology and human computer interaction have repeatedly demonstrated that VR environments have the capacity to enhance motivation and emotional involvement, which are critical predictors of success in this domain (Bart *et al.*, 2008; Đorđević *et al.*, 2024; Merchant *et al.*, 2014; Meyer & Omdahl, 2019; Rianti *et al.*, 2020).

6. Conclusion

In summary, the findings indicate that the accident prevention school was received positively. The evaluations demonstrated a higher potential for FAPS and substantial added value in terms of programme satisfaction, perceived learning experience, and indicators of behavioural relevance when the VR module was integrated. The findings of this study further suggest that digital modalities, particularly VR, seem to add a heightened user preference and impact and hold considerable potential for accident prevention. The integration of VR and multi-perspective simulations appears to enhance engagement, perspective-taking and perceived learning durability in comparison with static reconstructions. This finding lends further support to the hypothesis that such methods facilitate behaviour-relevant learning outcomes. The impact of VR has

been demonstrated to have a positive effect, as evidenced by current findings from psychological research. This can be attributed to the creation of immersive experiences that involve pupils in active participation.

While the overall project content was well received and generated considerable interest, feedback from open text responses suggested that this impact could be further strengthened through relatively minor adaptations. The adaptations, which were based on factors including frequency of mention, feasibility, and expected impact, included extending the time pupils spend using the VR module and adding more scenarios from a driver's perspective. The findings underscore the imperative of aligning safety interventions with user experience design and operational constraints. Furthermore, emphasis is placed on the importance of effective communication of safety rationales, which is instrumental in facilitating attitude and behaviour change. The further development of road safety education is imperative in accident prevention.

CRediT contribution

Denis Preissner: Data curation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Vanessa Sarah Hilse:** Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Maria Pohle:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Writing – review & editing. **Nora Strauzenberg:** Conceptualization, Investigation, Methodology.

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Declaration of competing interests

The authors report no competing interests.

Declaration of generative AI use

The authors declare that no generative AI was used in this work.

Prior dissemination declaration

An earlier version of this work was presented at the 37th ICTCT conference, held in Berlin, Germany, on 23–24 October 2025.

Ethics statement

Questionnaires and workshops conducted within this research in the SOTERIA project involved human participants, including minors. Ethical and data protection requirements were addressed through an internal ethics and GDPR management framework. All procedures complied with GDPR principles and were reviewed in consultation with a data protection officer.

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Data availability statement

Data sharing is not applicable, as no datasets were generated or analysed for this study.

Code availability statement

Code sharing is not applicable, as no custom code or scripts were developed or used for this study.

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