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Assessing the effectiveness of an online cycling training for adults to master complex traffic situations

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ABSTRACT

Background: Acknowledging the significance of both subjective and objective safety in promoting cycling, there is a need for effective measures aimed at improving cycling skills among a broader population. Hence, the aim of the current study is to evaluate and investigate the impact of online cycling training targeted at adults.

Methods: An online cycling training consisting of three modules was developed to train safe behaviour in seven prototypical safety-relevant situations. 10,000 individuals were invited to participate, with 700 individuals completing the training. The effectiveness of the training was evaluated using a mixed-methods approach combining self-report measures with behavioural measures. Self-report measures were collected using four items of the Cycling Skills Inventory and knowledge-based questions. On a behavioural level, effectiveness was investigated using a virtual reality cycling simulator.

Results: Participants' self-reported cycling skills were evaluated before and after participation in the online training. Three out of four self-reported skills (i.e. predicting traffic situations, showing consideration, knowing how to act) improved on average, across participants. Moreover, participants who cycle less frequently benefited more from the training as they indicated their ability to recognise hazards, to predict traffic situations and to know how to appropriately after completion of the online training. Finally, all participants indicated that they felt more comfortable while cycling after completing the training.

In the training evaluation, it was found that the treatment group navigated through traffic more safely on a behavioural level, and/or possessed the required knowledge-based skills in three out of five evaluated situations.

Conclusion: These promising findings indicate that online cycling training is one potential avenue to develop cycling skills within a target audience of adult cyclists: not only on a knowledge level, but also on a behavioural level. Notwithstanding limitations, we conclude that an online cycling training can contribute to safer cycling and the promotion of cycling in general.

1. Introduction

Overall, the number of road fatalities and serious injuries across the European Union has decreased by 23% between 2010 and 2019. However, despite this decrease in overall fatalities and serious injuries, the percentage of cycling accidents leading to fatalities or serious injuries has increased from 7% (2010) to 9% (2019) (European Commission, 2021).

Cycling is given high priority in European transport policy because it offers solutions to environmental challenges, as well as contributing to healthier lifestyles. Considering the importance of subjective and objective safety to effectively promote cycling among a larger population, measures to improve cycling safety are urgently needed.

The most obvious way to improve cycling safety is by improving cycling infrastructure. However, in many urban areas, the development of cycling infrastructure lags behind the increase in cycling. Also, regardless of infrastructure, cycling in a safe manner requires a set of competences, including bodily fitness, steering and balancing skills, and knowledge of local traffic systems and rules (Larsen, 2017). Moreover,

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safe cycling in urban areas requires more elaborate cycling skills, including the ability to recognise traffic hazards and predict critical traffic situations ahead, which are equally important to prevent cycling accidents (de Winter et al., 2019).

In many cycling training programmes, these skills are not included because they focus on motor-tactical skills and knowledge of rules. Also, existing training programs focus mostly on children and even training programs for adults are conducted in-situ, thus limiting potential participation because such a program might not meet individuals' schedules and needs (Gálvez-Fernández et al., 2022).

Online cycling training could address these shortcomings on several levels. As an easily accessible option, the likelihood of participation for the intended audience of adults is greater. Also, online cycling training can include gaming elements that encourage and motivate users to stay engaged and complete the training.

Training cycling skills using an online training program could be an excellent way to improve cyclists' safety on urban roads while reaching a larger audience. Against this background, the study implements a real-life intervention by developing an online cycling training program. The study contributes to the existing research by investigating its effectiveness based on self-reported and recorded data during the completion of the online cycling training program; it also uses self-reported and objective behavioural data from a subsequent laboratory study using a virtual reality (VR) simulator.

The study thus aims to answer the following research question: What is the impact of online cycling training on cycling skills and safe cycling behaviour?

The remainder of this paper is structured as follows; First, it describes insights from previous research and formulates hypotheses. Second, it outlines the study's procedures and methods, which involved an online cycling training and the analysis of its effectiveness using a mixed-methods approach combining an online cycling training with a training evaluation using a virtual reality (VR) bicycle-simulator in a laboratory setting. Third, it presents the findings. Finally, results are discussed and implications for future research are derived.

2. Previous work and formulation of hypotheses

To better understand the effectiveness of training cycling skills, the study draws from several streams of literature: First, the concept of driving and cycling skills is discussed against the background of previous research. Second, findings from research on the effectiveness of cycling safety education are summarised. Third, insights from studies on the effectiveness of online cycling training are reported. Fourth, the usage of VR simulators as a tool for evaluation is discussed. Then, research gaps are identified and corresponding research hypotheses are proposed.

2.1. Safe driving behaviour, driving and cycling skills

To conceptualise driving skills as a predictor of safe driving, previous research distinguishes between several interdependent levels, assuming that safe driving behaviour requires a range of skills from actual driving skills to higher goal-oriented factors.

Hatakka et al. (2002) presents a four-level descriptive model conceptualising driver behaviour, known as the Goals for Driver Education (GDE) framework. The first and lowest level consists of skills concerning *vehicle manoeuvring*. These skills consist of driving and controlling the vehicle in a competent and automatised way. The second level consists of skills concerning the *mastery of traffic situations*. These skills include the knowledge of traffic rules, as well as the ability to perceive and predict other road-users' behaviour. The third level refers to the *goals and context of driving*. This relates to the trip purpose and situational aspects. The fourth and highest level of driving behaviour relates to *general skills and goals in life*. This broad category comprises personal motives (e.g. risk-seeking, fun), social norms, and values (e.g. hedonism, security). According to the GDE framework, safe driving behaviour requires all four levels of driving skills and any impairment of skills on a higher level negatively affects skills on a lower level.

Road safety education (RSE) encompasses all measures that aim to positively influence traffic behaviour. RSE emphasises the promotion of *knowledge* of traffic rules and situations, improvement of *skills* (including motor abilities, transformation of motor abilities into safe participation in traffic, estimation of distances and speed), and the strengthening of *attitudes and motives* towards risk awareness, personal safety, and the safety of other road users (ROSE 25 EU, 2005; Assailly, 2017). This set of measures largely corresponds to the GDE framework, except that no differentiation is made between GDE levels 3 and 4.

A more succinct way to categorise driving skills is to distinguish between two levels: driving skills and driving style (Elander et al., 1993; Lajunen and Summala, 1995). Driving skills encompass cognitive and motor-tactical skills (aligning with GDE levels 1 and 2), while driving style refers to motivational and attitudinal factors concerning traffic safety (corresponding to GDE levels 3 and 4).

An important distinction from a measurement perspective is the differentiation between objective skills – usually measured on a behavioural level – and self-reported skills, commonly assessed on the basis of a questionnaire (Ābele et al., 2018). Self-reported skills can be further classified into two main categories: knowledge-based skills, including the ability to recall rules, practice safe behaviour and recognise hazards; and self-reported skills, which pertain to an individual's own assessment of skills on a more abstract level.

While there is no standardised measure for objective skills and self-reported knowledge, de Winter et al. (2019) have developed the Cycling Skills Inventory (CSI) to measure self-reported cycling skills. The CSI is based on the Driving Skill Inventory (DSI, Lajunen and Summala, 1995), commonly used for measuring car drivers' self-reported driving skills. The CSI consists of 17 items, covering motor-tactical skills and safety motives. Motor-tactical skills comprise the handling of the bicycle and cycling performance in varying situations, e.g. with poor road conditions and diverse safety motives. Safety motives refer to the driving style, i.e. showing low-risk riding behaviour and complying with traffic rules.

This study focuses on the second level of driving skills as outlined in the GDE framework, with the objective of gaining insights on how to develop skills concerning cyclists' mastery of traffic situations. Through this, the study also addresses level 1 skills with the assumption that these skills are a necessary prerequisite for mastering traffic situations.

2.2. Effectiveness of cycling safety education

Road safety educational programs are one of the main strategies to improve traffic safety (Assailly, 2017). A systematic review showed that road safety training programs for adults are moderately effective; however, effectiveness increases when higher cognitive processes, such as risk perception or attitudes, are targeted rather than actual driving skills (Faus et al., 2022). The effectiveness of a cycling training can be assessed using various metrics, including the number of accidents, behaviour, knowledge, and attitudes (e.g. Richmond et al., 2013). Since accidents do not occur frequently, this metric has been subject to critical discussion (Colwell and Culverwell, 2002; Ducheyne et al., 2013). Behavioural outcomes refer to the actual performance of individuals when performing different cycling manoeuvres or self-reports of safe cycling behaviours, e.g. signalling and turning (e.g. Colwell and Culverwell, 2002; Savill et al., 1996). Knowledge refers to an understanding of safe cycling behaviour, which includes a wide range of topics: from knowledge about traffic signs, to wearing a helmet, to recognising hazards (e.g. Savill et al., 1996; Macarthur et al., 1998; McLaughlin and Glang, 2010). Attitudes refer to the perception of safe cycling behaviours, i.e. what defines safe cycling (e.g. Macarthur et al., 1998; Colwell and Culverwell, 2002). These metrics and definitions are not always clearly differentiated and corresponding items sometimes overlap. Consequently, a similar measurement might be categorised as behaviour in one study and as knowledge and attitude in another study.

A range of intervention studies has investigated the effectiveness of cycling skills training programs, targeting either children or adolescents (e.g. Ducheyne et al., 2013; Richmond et al., 2013; Mandic et al., 2018; Hatfield et al., 2019). A systematic review by Richmond et al. (2013) analysed the effect of cycling training programs for children on number and severity of accidents, behaviour, knowledge, and attitudes. The evaluated training programs consisted mainly of skills considered relevant due to practitioners' experience. None of the studies showed a reduction in injuries to cyclists due to accidents. Some studies found an improvement of safe cycling behaviour; however, few of the reviewed studies employed an experimental design with a randomised control trial. Knowledge about cycling safety was improved in several studies; in some cases, performance was compared against a control group. Attitudes were only investigated in two studies; these studies did not reveal any change in safe cycling attitudes.

Hatfield et al. (2019) criticised the fact that cycling education (for children) has barely changed over a longer time and is still mainly focused on vehicle handling and manoeuvring skills. They draw parallels with early car driver education, which primarily targeted driving skills, but had minimal impact on traffic safety. Hatfield et al. (2019) evaluated the effect of cycling training for children that taught vehicle handling and manoeuvring skills as well as higher-order skills like hazard awareness. As skills training could result in cyclists' overconfidence, this training aimed to avoid such an issue by making participants aware of risks and addressing the topic of invulnerability. The training was evaluated with a survey before and after the training, as well as a follow-up survey. The comparison between pre- and post-measures showed that knowledge about cycling safety and self-reported performance of some safe cycling behaviours increased (e.g. signalling when turning). However, no change in the reported frequency of safety and risky behaviour occurred (e.g. wearing headphones). Overconfidence decreased in the survey directly after the training, but increased to former levels in the follow-up survey. In conclusion, effects of cycling training on safety are mixed and there is a research gap concerning the effectiveness of a cycling training aimed at adults. Effectiveness so far has also only been investigated without considering the contents and skills taught in the training.

2.3. Online cycling training programs

Online cycling training programs facilitate the training of cycling skills predominantly on the level of attitudes, motives and knowledge, while reaching a larger audience than in-situ training. Regarding the present study's focus, this section reports only on studies about the development of skills at level 2, according to the GDE framework.

Kovácsová et al. (2020) developed and evaluated an online hazard anticipation training for experienced e-bike cyclists. The training consisted of video clips of potentially dangerous traffic situations; the participants' task was to identify the hazard. The treatment group was given an explanation of the hazardous situations, whereas the control group was asked general questions about traffic behaviour. The training was evaluated by measuring participants' speed and accuracy in recognising hazards in a hazard detection test. Trained participants were faster at recognising hazards, yet did not detect more hazards than the control group.

A video-based cycling training aimed at increasing situational awareness in traffic situations for children was developed by Lehtonen et al. (2017a). Situational awareness describes the perception and understanding of a situation and is based on three levels: (1) perception of the environment, (2) comprehension of the situation, and (3) prediction of the prospective situation (Endsley, 1995). In the cycling training, participants were shown video clips of cycling situations and had to identify the location of potential hazards, i.e. other road users (Lehtonen et al., 2017a). The participants were then shown the correct answer and were provided with additional feedback. Participants' accuracy in detecting potential hazard improved, suggesting that the training enhances skills in situational awareness.

In summary, limited research exists on the effectiveness of online, self-directed cycling training (Lehtonen et al., 2017b; Kovácsová et al., 2020). Most intervention studies investigated the effectiveness of an in-situ training (Ducheyne et al., 2013; Mandic et al., 2018), or a mix of in-situ training and classroom-style teaching (Hatfield et al., 2019). Furthermore, to our knowledge, no empirical study has yet assessed the effectiveness of online cycling training using behavioural measures.

2.4. VR simulators as a tool for evaluation

There are several reasons to employ simulators (e.g. Kaptein et al., 1996); designs may not be available in reality, or the sequence of tasks to complete may not be available in a real-life route. Furthermore, simulators allow for the evaluation of behaviour in a safe and controlled environment and provide experimental control.

Several differences exist between bicycle simulators. First, some simulators rely on a virtual reality headset to project virtual environment (e.g. O'Hern et al., 2017; Nazemi et al., 2021); other bicycle simulators use a series of monitors to project virtual environment (e.g. Keler et al., 2018; WIVW, 2024). Second, some simulators allow for steering, as well as pedalling (e.g. O'Hern et al., 2017; WIVW, 2024), whereas other simulators did not allow steering to avoid motion sickness (e.g. Nazemi et al., 2021). Third, some simulators employ a stand, and thus do not employ body motion for steering (e.g. O'Hern et al., 2017; Nazemi et al., 2021). Other simulators stand on a motion platform or use other means to provide users with realistic steering, rolling, yawing, and swaying motion (Haasnoot et al., 2023). The latter type of bicycle simulators aim to overcome the mismatch that arises between cues from the vestibular system and the visual changes in VR that can result in motion sickness.

The validity of simulators can be assessed in several ways (Kaptein et al., 1996). Task-based validity refers to whether the validity of a simulator is sufficient for the task at hand. Actual validity refers to whether the behaviour in the simulator is similar to reality (e.g. cycling speed); relative validity indicates that the direction or relative intensity of the effect is the same as in reality (e.g. changes in lateral position).

O'Hern et al. (2017) specifically evaluated lane position, lateral position of cyclists when parked cars are present, speed reduction at intersections, and head movements for a bicycle simulator equipped with a head-mounted display. They found that their simulator was able to replicate lateral position along different cycling facilities and relative to passing vehicles (actual validity), but that cycling speeds in the simulator were lower than reality. Nevertheless, speed reductions on the intersection approach were the same as in reality (relative validity). Nazemi et al. (2019) evaluated subjective safety, but also looked at the choice of speed along different types of cycling infrastructure, and evaluated head movement. Between infrastructure types, differences in speed could be distinguished (relative validity). Also, participants tended to check for traffic at intersections, as would be necessary in real-life cycling (absolute validity). Chand et al. (2024) evaluated the lateral and velocity of cyclists along routes with different widths and examined how cyclists behave in dooring zones. Participants rode on the left edge of the bicycle lane (adjacent to traffic) when passing the door zone, regardless of bicycle lane width. On narrower cycling lanes, participants tended to leave the bicycle lane, while on wider lanes, participants either stopped or safely passed through the door zone, dependent on the time to door (task-based and relative validity).

These selected studies show how simulators have been employed to explore scenarios evaluating cycling speed and lateral position under controlled conditions. Nevertheless, whether bicycle simulators can accurately capture other behaviours such as gestures, and the sequence of manoeuvrers when turning left or traversing roundabouts, remains open for further research.

2.5. Research gaps and formulation of hypotheses

To sum up, research literature reveals several gaps: (1) few studies evaluated the effectiveness of a cycling training for adults; (2) until now, no studies have investigated the effectiveness of online cycling training on self-reported skills, (3) effectiveness of online training on knowledge-based cycling skills has only been tested in a few studies; and (4) empirical evidence of the impact of online cycling training on actual cycling behaviour is missing.

This study addresses these research gaps to develop and implement online cycling training designed specifically to develop cycling skills for adults. The empirical study is designed to the test the following hypotheses:

- Hypothesis 1: Online cycling training improves self-reported cycling skills.
- Hypothesis 2: Online cycling training improves knowledge-based cycling skills.
- Hypothesis 3: Online cycling training improves cyclists' safe riding behaviour (objective skills).

To test these hypotheses, online cycling training is evaluated using three measures: First, self-reported cycling skills are measured before and after the online cycling training; second, knowledge-based cycling skills are measured based on task performance in the cycling training; and third, objective cycling skills are evaluated in a VR simulator study.

3. Methodology & materials

3.1. Training program

3.1.1. Traffic situations and cycling skills

The primary aim of our online training program is to enhance cyclists' abilities in safely navigating urban traffic. These abilities encompass skills matching GDE level 2 (Hatakka et al., 2002). This includes hazard perception, situational awareness, and automating specific skills (level 2). We thus focus on improving recognition of typical situations and required 'vehicle control' in these situations, which encompass both motor and control skills (level 1). This online cycling training consists of seven situations, selected because they have led to injuries or fatalities according to an analysis of accident statistics, and because cycling safety experts identified a need to improve cyclists' skills in these situations based on focus-group interviews (bfu, 2021; van Eggermond et al., 2022, 2023). Analyses revealed that a large percentage of accidents involve right-of-way; three situations thus focused on right-of-way issues in different settings.

The first situation involves right-of-way on a curved priority road. Required skills in this situation include signalling the intention to continue along the priority road, shoulder-checking for overtaking traffic, looking ahead, and scanning right for oncoming vehicles.

Closely related to this situation are right-of-way situations occurring at Y junctions. The most important skill in this situation is to perform a shoulder check, followed by signalling intent.

The third right-of-way situation involves different priority situations at unsignalised intersections, including intersections in slow-speed zones. Relevant skills include the ability to determine priority order, looking ahead, scanning left and right, and adjusting speed according to sight distances.

In roundabouts without cycling facilities, it is recommended that cyclists ride in the centre of the (left-hand) lane. Furthermore, cyclists should move to the centre of the lane prior to entering the roundabout, and prior to doing so, perform a shoulder check and signal their intent.

The fifth situation involves on-street parking; on roads with on-street parking, it is recommended that cyclists maintain at least a 1-metre (3-foot) distance from parked cars to avoid dooring accidents.

The sixth situation pertains to making a left turn, which requires varying skills depending on the actual cycling infrastructure. Typically, it is expected that cyclists perform a shoulder check, signal their intent, move to the centre of the lane (changing lanes, if available), look ahead to check for oncoming traffic on the left side, and continue if there is no oncoming traffic.

The last situation considers the awareness of blind spots and safe behaviour in blind-spot situations, especially with trucks and buses.

We propose that, if cyclists are to navigate safely through these situations (level 2), it is necessary to possess sufficient vehicle control (level 1). Vice versa, if cyclists exhibit a set of required motor and control skills in certain situations, we observe their ability to navigate safely in traffic and confirm that they possess level 2 competences. For example, consider a situation at an unsignalised intersection where a potential right-of-way situation arises (level 2). It begins with recognising the intersection as a hazard, followed by actions such as adjusting speed, scanning left and right, and determining priority for proceeding. Each situation was defined in a similar fashion, and cyclists were asked to state their expected behaviour in these situations.

3.1.2. Procedures

The online training consisted of three modules: two training modules and a final test to test the acquired skills. Fig. 1 displays the training procedure. Potential participants were invited by postal mail to participate; The invitation to each module was separated by approximately a one-week time gap and sent via e-mail. Participation was encouraged through a raffle, in which 25 prizes (vouchers) with a total value of CHF 2500 were available to winners.

Cycling skills for the seven situations were trained with a total of 24 tasks. For each situation, a series of photos, videos or sketches was developed to support questions and provide feedback. The tasks consisted of different question types, such as single-choice questions, rank-order tasks, classification tasks, or identification of relevant spots. The training was developed in an iterative process where content, structure, and design were repeatedly tested with user tests, and was implemented using the survey software, Qualtrics.

Each training module consisted of 12 tasks. Each correct answer was awarded 10 points; partially correct answers were given 5 points. A score of 100 points was required to complete a training module. Each training module could be repeated twice. The final test consisted of seven tasks from previously learned material. A score of 60 points was required to complete the final test, which could be repeated once.

The concept of the online cycling training was based on the concept of gamification (Hamari et al., 2014; Wallius et al., 2022). Established behaviour-change techniques such as feedback, monitoring, and tangible (as well as intangible) incentives were used to ensure users' engagement with the training. In Fig. 2, an example is provided from the training program, showing (from left to right) an example question, feedback for a correct answer, and feedback for an incorrect answer.

3.1.3. Measures and data analysis for self-reported and knowledge-based cycling skills

The online cycling training effect on self-reported cycling skills was measured with four items in the Cycling Skill Inventory (de Winter et al., 2019). The CSI itself consists of 17 items and measures skills along three dimensions: motor-tactical skills (e.g., controlling the bicycle), safety-related skills (e.g. adjusting speed to conditions), and traffic-rule skills (e.g. obeying traffic signals). In its initial conception, cyclists were asked to rate their ability on each of the items on a 5-point scale, ranging from 1 (definitely weak) to 5 (definitely strong).

Participants filled out a self-assessment prior to starting the training and after completing the whole training program. The items selected from the CSI reflect the skills practised in the cycling training: (1) Recognising hazards in traffic, (2) predicting traffic situations ahead, (3) showing consideration for other road users, and (4) knowing how to act in certain traffic situations. Additionally, the item, "Feeling comfortable while cycling", was included to measure an overall sense of mastery at cycling on urban roads. Specifically, the questions were

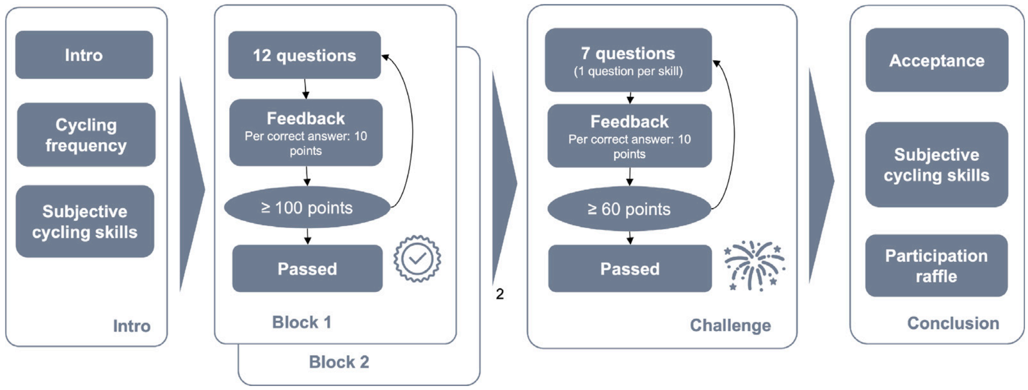


Fig. 1. Outline of the online training program, which comprises two training modules followed by a challenge. Participants' self-reported skills are assessed both before the initial block ('Introduction') and on completion of the training ('Conclusion').

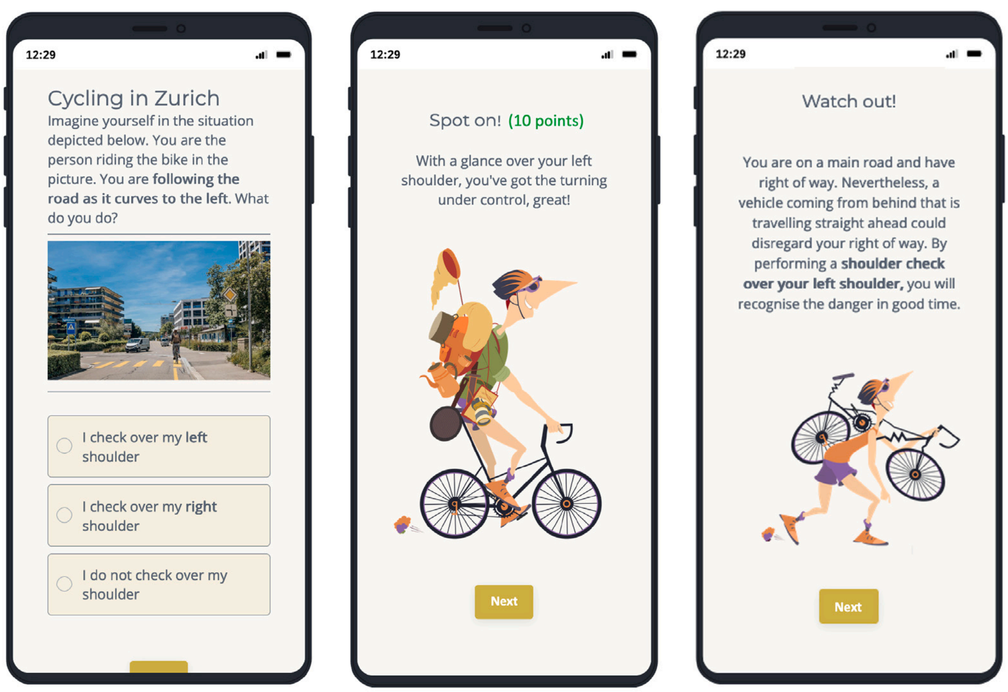


Fig. 2. Screenshots of the online training program with, from left to a right, a question, feedback when correct, and feedback when an incorrect answer was provided. The original training program is in German; the English translation is provided as an illustration).

phrased e.g.: 'While cycling in the city, I am able to recognise hazards,' with responses given on a five-point Likert scale ranging from 1 (Not at all) to 5 (Very).

To evaluate knowledge-based cycling skills, task performance in the online cycling training was measured. The correct answers and the achieved score were measured after the first round in each training module. Additionally, the number of repetitions of each module was registered.

Furthermore, to evaluate the effect of the repeated measures design, we analysed the results with ordinal logit models, with cycling training as a fixed effect and the individual as a random effect. Additional interactions (e.g. cycling frequency) were explored as an interaction term in the analysis. Performance in the tasks was analysed with McNemar's test between the tasks for each skill.

3.2. *Training evaluation: Virtual reality bicycle simulator study to measure objective skills on a behavioural level*

3.2.1. *Set-up VR cycling simulator*

The VR cycling simulator consisted of several hardware and software components. The hardware included a head-mounted display (Oculus Rift) and a gaming laptop. The software included a virtual environment rendered in Unity. The VR cycling simulator was provided by *Virtual Reality Learning*[1] and is used for cycling safety education. Impressions of the cycling simulator are shown in Fig. 3.

This simulator has not been validated quantitatively, unlike some of the previously mentioned simulators, (e.g. O'Hern et al., 2017), but has been used extensively in road safety education on topics varying from

[1] Virtual Reality Learning GmbH, https://www.vr-bike.info/

(a) Cycling simulator with participant (b) Cycling simulator: side view

Fig. 3. Virtual cycling simulator.

training blind spots to informing about dooring dangers. Hence, we expect that the simulator can be used as a tool for evaluation, especially in a *between subjects* design where both groups use the same simulator. Nevertheless, evaluating behaviour along absolute measures, such as choice of speed or choice of lateral position, is not possible without further validation of this specific simulator.

3.2.2. Procedures VR simulator study

The VR simulator study is based on a between-subjects experimental design that allows evaluation of the online cycling training effect by comparing a treatment group to a control group. The assignment of subjects to treatment and control group is based on non-random criteria, recruiting subjects from training participants for the treatment group and subjects from the general population for the control group. As such, the procedures follow those of a quasi-experimental design that has the advantage of higher external validity due to the real-world intervention setting. The disadvantages of lower internal validity and possible related limitations due to confounding variables are limited by balancing the two samples based on selected criteria (see section sample 4.2.1).

The simulator study experiment consisted of five steps. The main part of the experiment was cycling through a test track in the VR bicycle simulator (step 3). This test consisted of six scenarios, depicted in Fig. 5, covering five of the seven skills addressed in the online training. Two skills ("right-of-way at Y-junctions" and "right-of-way on curved priority roads") were not included in the VR simulator study — these scenarios were not available. Directions in two scenarios ("traversing roundabouts" and "performing left turn") were provided by a pop-up inline arrow, indicating the route to the participant. The total duration of the experiment was approximately 45 min and consisted of the following steps:

- Step 1: Information on the purpose and procedure of the experiment (Informed Consent). The cover story explained that the study compares cycling in VR to cycling in reality.
- Step 2: Instruction of VR bicycle simulator and cycling through a training section.
- Step 3: Cycling through a test track in the VR bicycle simulator: following the training track, participants cycled through the test track with six situations (see Fig. 4). The test track led along a continuous route on urban roads.
- Step 4: Completing questionnaire: after cycling through the test track, participants completed a questionnaire measuring their evaluation of safe behaviours for the previously encountered situations, their current well-being, and feelings of presence in the VR simulation consisting of feelings of immersion and control (Kronqvist et al., 2016), previous experience with VR, cycling skills (de Winter et al., 2019), feeling comfortable when cycling on different types of streets (Dill and McNeil, 2013), questions about current mobility behaviour, as well as a manipulation check.
- Step 5: Debriefing

3.2.3. Measures and data analysis

Three different methods were used to collect data. Participants' cycling behaviour was measured using observational and sensor data from VR. Observational data was documented based on a structured observation protocol during and after the experiment (based on video recordings) by two independent observers not privy to treatment and control conditions. Documentation of behaviours by the two observers was compared, and inconsistent categorisation resolved. Sensors recorded data by means of continuous data collection and so-called trigger points. These sensors recorded the participant's position every 10th of a second, allowing for speed calculation and lateral position. Knowledge-based cycling skills were measured with a questionnaire after completion of the VR experiment. In the questionnaire, participants evaluated the situations presented in the test track. A summary of the various measures collected for each scenario, along with the corresponding methods, is provided in Table A.10.

4. Results

4.1. Evaluation based on self-reported cycling skills and knowledge-based skills

4.1.1. Sample

A detailed overview of the descriptive statistics of the sample is provided in Table 1. A random selection of 9670 subjects, aged between 18 and 59, was chosen from the Zurich city registry and invited via mail to participate in the online training program. Of the 9670 persons invited, 1182 participants completed the first module, resulting in a response rate of 12%. Subsequently, 723 participants completed all three modules, including the final test, resulting in a final response rate of 7.5%. Hence, the completion rate is 61%. The participants consisted of 53% men, 46% women, and 1% diverse gender. The mean age was 35.5 years; the median age was 34 years. 72% of participants cycled several times per week, 20% cycled several times per month, and 8% cycled once per month or less.

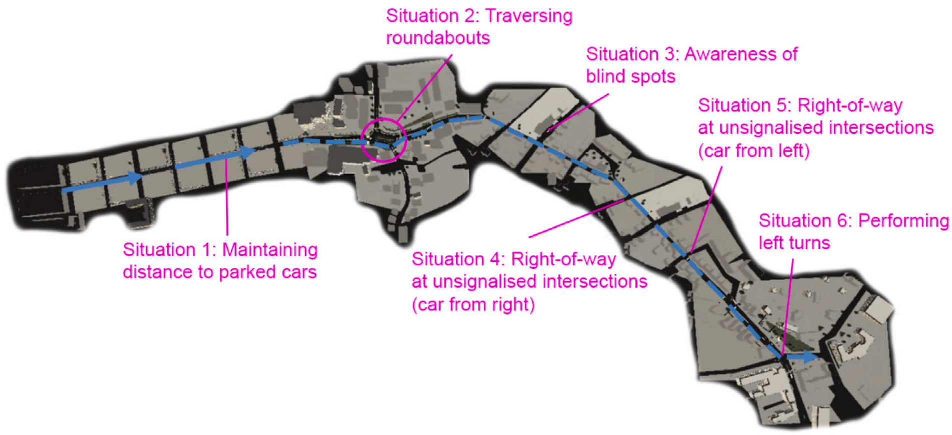
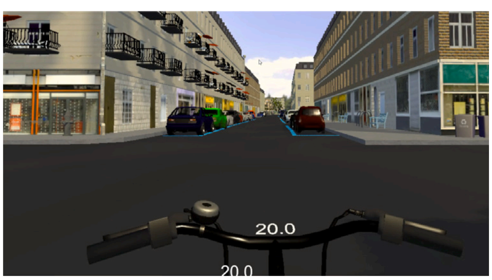
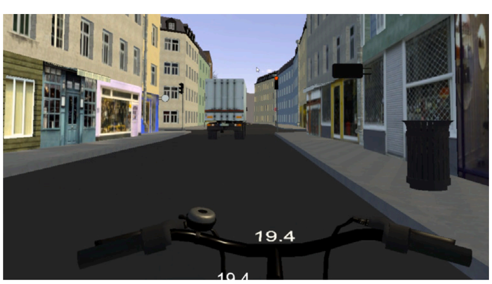


Fig. 4. Virtual reality test track.



(a) Scenario 1: lateral parked cars

(b) Scenario 2: traversing roundabouts



(c) Scenario 3: recognising a blind spot situation

(d) Scenario 4: right-of-way at unsignalised intersection (car from right)

(e) Scenario 5: right-of-way at unsignalised intersection (car from left)

(f) Scenario 6: performing left turn

Fig. 5. Scenarios.

Table 1
Participation in online training program.

	Invited participants		Start block 1		Completes block 1		Completes block 2		Completes final test	
	n	%	n	%	n	%	n	%	n	%
Gender										
Female	4691	49	556	39.7	532	45	392	48	325	45.9
Male	4979	51	602	43	577	49	417	51	374	52.8
Divers			24	1.71	21	1.8	12	1.5	8	1.13
Not provided			219	15.6	52	4.4	1	0.1	1	0.14
Age group										
18–29	3594	37	354	25.3	340	29	252	31	212	29.9
30–39	3291	34	459	32.8	439	37	312	38	276	39
40–49	1926	20	260	18.6	259	22	188	23	160	22.6
50–59	859	9	82	5.85	75	6.3	59	7.2	51	7.2
Other			6	0.43		0		0		0
Not provided			240	17.1	69	5.8	11	1.3	9	1.27
Cycling frequency										
Multiple days per week			884	63.1	815	69	588	72	510	72
Multiple times per month			267	19.1	237	20	161	20	140	19.8
Once a month or less			152	10.8	130	11	73	8.9	58	8.19
None			67	4.78		–		–		–
Not provided			31	2.21		–		–		–

Table 2
Results of ordinal logit models evaluating the effect of the online training on subjective skills with training and cycling training as fixed effects and participant as random effect.

Variable	Recognising hazards		Predicting traffic situations		Showing consideration	
	Beta (Std. Error)	OR (95% CI)	Beta (Std. Error)	OR (95% CI)	Beta (Std. Error)	OR (95% CI)
Cycling frequency [Low]	−1.157 (0.23)***	0.315 (0.2,0.49)	−0.889 (0.24)***	0.411 (0.26,0.66)	1.101 (0.26)***	3.006 (1.82,4.96)
Training [After]	−0.152 (0.14)	0.859 (0.66,1.12)	0.307 (0.14)*	1.359 (1.04,1.78)	0.471 (0.14)***	1.602 (1.22,2.11)
Cycling frequency [Low] × Training [After]	0.904 (0.26)***	2.468 (1.49,4.1)	0.7 (0.26)**	2.014 (1.21,3.36)	−0.281 (0.28)	0.755 (0.44,1.3)
Thresholds						
Intercept (Not at all | 2)	−8.725 (1.03)***	0 (0,0)	−8.979 (1.04)***	0 (0,0)	−8.709 (1.06)***	0 (0,0)
Intercept (2 | 3)	−6.177 (0.37)***	0.002 (0,0)	−6.302 (0.37)***	0.002 (0,0)	−6.101 (0.41)***	0.002 (0,0)
Intercept (3 | 4)	−3.581 (0.2)***	0.028 (0.02,0.04)	−3.054 (0.19)***	0.047 (0.03,0.07)	−2.991 (0.19)***	0.05 (0.03,0.07)
Intercept (4 | Very much)	0.003 (0.12)	1.003 (0.79,1.27)	1.06 (0.14)***	2.887 (2.19,3.8)	0.314 (0.13)*	1.369 (1.06,1.77)
N	1410		1410		1410	
R2 marginal	0.026		0.021		0.034	
R2 conditional	0.406		0.516		0.511	
AIC	2623.2		2705.4		2593.6	

Table 3
Results of ordinal logit models evaluating the effect of the online training on subjective skills (continued).

Variable	Knowing how to act		Feeling comfortable	
	Beta (Std. Error)	OR (95% CI)	Beta (Std. Error)	OR (95% CI)
Cycling frequency [Low]	−1.082 (0.21)***	0.339 (0.23,0.51)	−0.983 (0.28)***	0.374 (0.22,0.64)
Training [After]	0.388 (0.13)**	1.474 (1.13,1.91)	0.542 (0.13)***	1.719 (1.33,2.22)
Cycling frequency [Low] × Training [After]	0.819 (0.25)**	2.269 (1.39,3.71)	1.353 (0.25)***	3.868 (2.36,6.35)
Thresholds				
Intercept (Not at all | 2)	−7.17 (0.61)***	0.001 (0,0)	−6.788 (0.37)***	0.001 (0,0)
Intercept (2 | 3)	−4.762 (0.26)***	0.009 (0.01,0.01)	−3.392 (0.21)***	0.034 (0.02,0.05)
Intercept (3 | 4)	−2.872 (0.17)***	0.057 (0.04,0.08)	0.051 (0.15)	1.053 (0.78,1.42)
Intercept (4 | Very much)	0.649 (0.12)***	1.914 (1.52,2.4)	3.414 (0.2)***	30.401 (20.38,45.36)
N	1410		1410	
R2 marginal	0.042		0.032	
R2 conditional	0.369		0.668	
AIC	2778.3		3510.2	

4.1.2. Impact of training on self-reported cycling skills

To evaluate the online cycling training's effect, regression models were estimated, including the first and second assessment of cycling skills on an individual level. The considered covariates included cycling frequency and measurement time (before starting training/after completing training). The results of the ordinal logit models accounting for repeated measures (training and cycling training as fixed effects and participant as random effect) are shown in Tables 2 and 3.

For the skill 'Recognising hazards in traffic' less frequent cyclists are only about 31.5% as likely to recognise hazards in traffic compared to frequent cyclists: they are about 68.5% less likely to recognise hazards in traffic. No significance of the training could be determined, as indicated by the variable 'Training [After]'. However, there was a significant interaction effect for individuals cycling less frequently after the intervention. For these individuals, the odds of recognising hazards increased by 146.8% compared to individuals cycling frequently.

For the skill 'Predicting traffic situations ahead', less frequent cyclists are about 41% as likely to recognise hazards compared to frequent cyclists: they are about 59% less likely to predict traffic situations. After the training, all participants are 36% more likely to predict traffic situations. This effect is more pronounced for individuals cycling less frequently. For these individuals, the odds of predicting traffic situations ahead after the intervention increased by 101.4% compared to individuals cycling frequently.

For the skill 'Showing consideration to other road users', individuals with low cycling frequency are about 200.6% more likely to show more consideration to other road users. After the training, all participants are 60.2% more likely to show consideration. No significant interaction

Table 4
Overall score in modules.

	n	Mean	SD	% of total score	Median	Min	Max
Module 1	708	82.9	16.4	69%	80	30	120
Module 2	695	107.0	12.6	89%	110	50	120
Final test	705	66.0	5.9	94%	70	40	70

Note. One question in module 2 and in the final test were not compulsory. 15 and 3 participants, respectively, omitted this question and were thus excluded from the analysis.

effect was observed between cycling frequency and training after the training.

For the skill 'Knowing how to act in certain traffic situations', individuals with low cycling frequency have about 33.9% of the odds of predicting traffic situations compared to frequent cyclists, indicating they are about 66.1% less likely to predict traffic situations. After the training, all participants are 47.4% more likely to know how act in certain traffic situations. This effect is more pronounced for individuals cycling less frequently, as indicated by a significant interaction effect. For these individuals, the odds of knowing how to act ahead after the intervention increased by 126.9% compared to individuals cycling frequently.

4.1.3. Impact of training on knowledge-based skills

Overall score. Participants' average scores after completing a module for the first time are displayed in Table 4. Following the first completion of training module 1, participants achieved an average of 69% of the total score. A total of 524 participants had to repeat training module 1 once; six participants repeated the module twice. After the first round of training module 2, participants scored an average of 89% of the total score. A total of 102 participants had to repeat training module 2 once, and two participants repeated it twice. After the first round of the final module, participants scored an average of 94% of the total score. 50 participants repeated the final test.

Performance in tasks. Participants were evaluated for proof of improvement. To this end, trained tasks indifferent situations deemed of equal difficulty and focused on the same skills were evaluated using a pairwise McNemar test. In the following situations and tasks, this was the case: 'Right-of-way at unsignalised intersection', 'Maintaining distance to parked cards', 'Awareness of blind spots' and 'Performing left turns'. In the remaining situations, tasks were not deemed similar enough and/or not of similar difficulty.

The participants' performance in the evaluated situations improved over the course of the training. Table 5 displays progress as the percentage of correct answers in each situation, along with the results of Cochran's Q-Test, followed by the pairwise McNemar test results. The tests compare the first task of each situation with each subsequent task.

For instance, in the situation 'Recognising blind spots', 49% of participants provided the correct answer in the first task. This improved to 94% in the second task and further to 99% in the challenge task. A Cochran's Q test was conducted to examine differences in proportions across the tasks, yielding significant results, $Q(705) = 895.378, p < .001$, indicating significant differences among the conditions. Subsequently, a pairwise McNemar test was conducted, revealing significant differences between task 1 and tasks 2, 3, and 4, with adjusted p-values of $p < .001$.

For the other situations evaluated with pairwise McNemar tests, a similar pattern is observed; after completing the first task, participants perform well in subsequent tasks. The rate of learning improvement decreases between subsequent tasks.

In the situations 'right-of-way on curved priority roads' and 'right-of-way at Y-junctions', only small differences were observed. Nevertheless, in the challenge tasks, participants recognised that certain manoeuvrers should be performed in these situations, as indicated by the high percentage of correct answers.

4.2. Training evaluation

4.2.1. Sample

Participants of the VR simulator study were recruited as follows; After completion of the online training, participants were asked to indicate whether they were interested in participating in future studies related to transportation and mobility. These participants were invited to the VR simulator study as part of the treatment group. Of the 408 who expressed interest in participating, 121 were invited to the study. Priority was given to infrequent cyclists: people who cycle "multiple times per month" or less. The sample for the control group was recruited over social media channels. To ensure comparability, samples were balanced for cycling frequency, level of education, and gender. All participants completed a shortened and adapted version of the Motion sickness susceptibility questionnaires MSSQ (Golding, 2006) to screen out participants with a susceptibility to motion sickness.

A total of 205 people started the screening questionnaire, of which the following were excluded: 16 because they do not cycle, 18 had a susceptibility to motion sickness, 63 did not fit the required demographics (age, place of residence, work in related industry), and 25 were screened out because they were frequent cyclists ("multiple days per week"); this ensured an equal distribution of cycling frequency among the samples. Seven people did not enrol for the study, and six were no-shows or cancellations.

Table 6 provides an overview of participant demographics and cycling frequency in the VR evaluation study. The table provides an overview of the total sample, as well as a breakdown of the sample into treatment and control group.

The majority of participants were male, constituting 57.1% of the total sample. In the treatment group, 50% were male, while in the control group, the percentage was higher at 66.7%. Conversely, female participants represented 42.9% of the total sample, with 50% in the treatment group and 33.3% in the control group. The age distribution shows a diverse sample, with the highest percentage being in the 30–39 age group for both treatment and control group. The majority of the participants cycled multiple days per week (39 individuals), and represented 66.7% of the treatment group and 33.7% of the control group. Meanwhile, 24 participants cycled multiple times per month, and constituted 35.1% of the treatment group and 46.4% of the control group.

For participants who participated in the online training, average time between completion of the training and the VR simulator study was 27.3 days (median 26 days, standard deviation 10.3 days).

To ensure comparability between participants of both groups, only participants who cycled at least multiple times per month were included in the analysis (five participants were removed from the control group). Furthermore, participants who indicated that they were aware of the purpose of the VR simulator study were excluded (two participants from the treatment group). Overall, control and treatment groups did not differ significantly in cycling frequency, age, and gender. Finally, four respondents were excluded in the analysis of the VR-trajectory data due to data recording issues (three participants from the treatment group, one from the control group). Excluding these participants did not influence the overall results (questionnaire, trigger point).

4.2.2. Evaluation of effectiveness

The remainder of this section will discuss the results of the VR experimental study in more detail with regard to the five trained skills. These results are based on behavioural data (VR-data), observational data, and questionnaire data.

Table 5
Performance in tasks for each cycling skill. Percentages indicate the percentages correctly answered; p-values indicate whether the difference to the first task is significant and are calculated with a pairwise McNemar test. Situations without statistical tests were deemed too different to test and/or not of the same difficulty.

Cycling skills	Cochran's Q	Task 1	Task 2	Task 3	Task 4	Challenge task
Tasks focusing on the same subskills						
Right-of-way (vehicle from the right)	Q(705) = 812.994 p <.001	53%	95% (Block 1) p <.001	90% (Block 2) p <.001		100% p <.001
Distance to parked cars	Q(705) = 475.927 p <.001	59%	95% (Block 2) p <.001	–	–	99% p <.001
Turning left	Q(705) = 442.61 p <.001	37%	86% (Block 1) p <.001	82% (Block 2) p <.001		
Recognising blind spots	Q(705) = 895.38 p <.001	49%	94% (Block 2) p <.001	99% (Block 2) p <.001	–	99% p <.001
Tasks focusing on different subskills						
Right-of-way on curved priority roads	–	82%	84%	87%	93%	98%
Right-of-way at Y-junctions	–	83%	92%	97%		96%
Traversing roundabouts	–	52%	52%	65%	58%	69%

Table 6
Sample Virtual Reality evaluation study.

	Total		Treatment group		Control group	
	n	%	n	%	n	%
Gender						
Female	27	42.9	18	50	9	35.7
Male	36	57.1	18	50	18	64.3
Age group						
18–29	20	31.7	12	33.3	8	29.6
30–39	23	36.5	14	38.9	9	33.3
40–49	12	19.0	7	19.4	5	18.5
50–59	7	11.1	3	8.3	4	14.8
60 years or older	1	1.6	0	0.0	1	3.7
Cycling frequency						
Multiple times per month	24		12	33.3	12	44.4
Multiple days per week	39		24	66.7	15	55.6

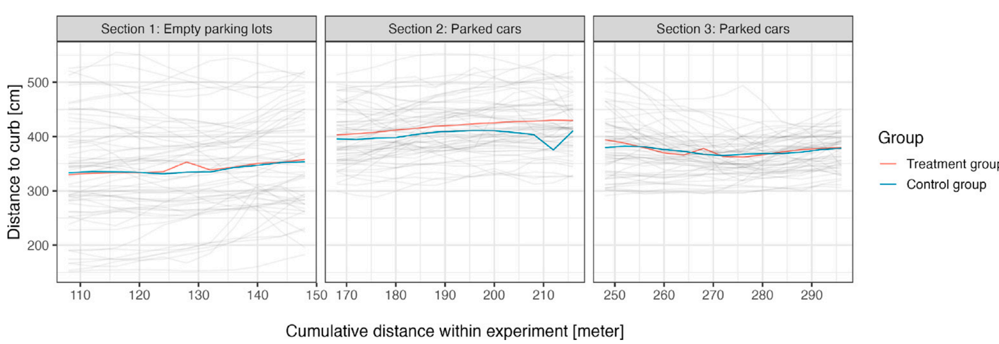


Fig. 6. Evaluation of lateral position at parked cars. Grey lines represent the lateral position of individual participants.

Lateral position. When cycling adjacent to parked cars, it is recommended keeping at least a 1-metre (3-feet) distance. To evaluate whether participants kept a distance from parked cars, the experiment contained three sections. First, participants cycled through a section with parking lane markings, but without parked cars. Subsequently, two sections followed with parked cars. Fig. 6 shows the distance to the curb (in centimetres) and the distance traversed within the experiment. It can be seen that participants cycled, on average, 340 cm from the curb if there were no parked cars. When parked cars were present, both the treatment group and the control group increased the distance to the parked cars in the second section. The distance to parked cars was smaller in the third section.

To evaluate whether the distance between the sections and groups differed significantly, a multilevel regression model was estimated, including the section and training as fixed effects and the participant as a random effect (see Table 7). The model takes into account the average distance to the curb in 4-metre bins (i.e. averages over ranges of 4 metres). The intercept of 346 cm indicates the distance kept to the curb in the first section. This distance increases in the second section by 65 cm. The treatment group kept 30.7 cm more distance from the curb in the first section as compared to the control group and 26 cm more distance from the curb in the second section compared to the control group.

The questionnaire did not reveal a significant difference in the choice of lateral position between the groups. Fisher's Exact Test was applied to the count data to investigate the hypothesis that there is no association between training and the choice of lateral position (cycling in the middle of the road). The resulting p-value was 0.587. The difference to parked cars could not be measured objectively through observation and was thus not pursued further.

Roundabouts. In single-lane roundabouts, cyclists are advised to ride in the centre of the lane. Prior to entering a roundabout, cyclists are

Table 7
Results of multilevel regression model for lateral position at parked cars.

Variable	Estimate (Std. Error)
(Intercept)	345.977***
	(10.886)
Treatment group	−26.245+
	(14.556)
Parked cars [Second section]	65.220***
	(3.573)
Parked cars [Third section]	25.561***
	(3.573)
Treatment group: Parked cars [Second section]	30.687***
	(4.778)
Treatment group: Parked cars [Third section]	26.179***
	(4.778)
SD (Intercept id)	53.863
SD (Observations)	44.472
Num.Obs.	2183
R2 Marg.	0.191
R2 Cond.	0.672
AIC	22 980.9
BIC	23 026.4
ICC	0.6
RMSE	43.84

+ $p < 0.1$, *$p < 0.05$, **$p < 0.01$, *** $p < 0.001$

Table 8
Results of multilevel regression model for cycling speed.

Variable	Estimate (Std. Error)
(Intercept)	17.507***
	(0.580)
Treatment group	−1.350+
	(0.776)
At intersection	−3.407***
	(0.332)
Treatment group: At intersection	−1.189**
	(0.444)
SD (Intercept id)	2.725
SD (Observations)	3.041
Num.Obs.	767
R2 Marg.	0.234
R2 Cond.	0.575
AIC	4034.2
BIC	4062.1
ICC	0.4
RMSE	2.93

+ $p < 0.1$, *$p < 0.05$, **$p < 0.01$, *** $p < 0.001$.

expected to perform various manoeuvres, such as shoulder-check and signalling left. When exiting the roundabout, cyclists are expected to a shoulder-check and signal right.

However, most participants encountered challenges in performing these manoeuvres on the VR bicycle simulator. This is further outlined in the 'Limitations' section.

Analysis of the VR data with predefined trigger points revealed that cyclists in the treatment group cycled in the centre of the lane more often; 81% (n = 29) of the participants in the treatment group succeeded in cycling through all three predefined trigger points, whereas 63% (n = 17) of the participants in the control group cycled through all three trigger points. A Fisher's Exact Test was conducted on the frequencies for a two-sided alternative hypothesis, indicating that no significant differences exist between the groups ($p = 0.271$). Analysis of the lateral position based on VR data was not further pursued due to the large number of outliers.

Observational data included counts of shoulder-checks and hand signals when entering and exiting the roundabout. To estimate the differences between control and treatment groups, a score was calculated summing up the number of behaviours. Participants in the treatment group performed these behaviours more often (56%, n = 20) than participants in the control group (26%, n = 7). A Fisher's Exact Test was conducted on the frequencies for a two-sided alternative hypothesis, indicating significant differences between the groups ($p < 0.05$).

The questionnaire revealed a significant difference in the choice of lateral position between groups, with 60% of the participants in the treatment group stating that they would cycle in the middle vs 19% in the control group. A Pearson's Chi-squared test was conducted, and the results demonstrated a statistically significant association, $\chi^2(2) = 8.84$, $p = 0.002$.

Recognising blind spots. In blind spot situations, cyclists are advised to stop behind a truck.

Analysis of VR data showed a significant difference in the frequency of participants coming to a halt behind the truck. All participants in the treatment group stopped behind the waiting truck, whereas only 44% (n = 12) of the participants in the control group stopped. Pearson's Chi-squared test with Yates' continuity correction was conducted,; results demonstrated a statistically significant association ($p < 0.001$).

Observational data also confirmed VR data and revealed a significant difference in the frequency of participants coming to a halt behind the truck. All participants in the treatment group stopped behind the waiting truck, whereas only 44% (n = 12) of the participants in the control group stopped in this position. A Fisher's Exact Test was conducted on the frequencies for a two-sided alternative hypothesis, indicating that there were significant differences between the groups ($p < 0.05$).

The questionnaire revealed a significant difference in the frequency of treatment and control group participants willing to stop behind a truck. Pearson's Chi-squared test was conducted, with results demonstrating a statistically significant association ($\chi^2(2) = 15.8$, $p < 0.001$).

Right-of-way. At the intersection with a vehicle coming from the right and thus having right-of-way, differences between the treatment and control group could be identified.

Analysis of VR data revealed that participants in the treatment group reduced their speed as compared to participants in the control group (see Fig. 7). Participants from the control and treatment group cycled approximately 17 km/h. Prior to the intersection (starting at 1140 m in the experiment), all participants reduced their speed. To investigate whether these speed reductions were significant, multilevel regression models were estimated (see Table 8). The intercept is 17.51, representing the average cycling speed in km/h. At the intersection, all participants reduced their speed by 3.41 km/h. The treatment group further reduced their speed by 1.19 km/h at the intersection, a significant reduction.

Also, more participants from the treatment group (94%, n = 34) came to a full stop as compared to participants from the control group (36%, n = 17). Pearson's Chi-squared test was conducted; results demonstrated a statistically significant association ($\chi^2(2) = 6.74$, $p < 0.01$).

Observational data confirms these results with a Fisher's Exact Test conducted on the frequencies for a two-sided alternative hypothesis, indicating that there were significant differences between the groups ($p < 0.05$).

In addition, observational data included counts of keeping fingers on the brake, stopping with pedalling, and active braking. To estimate differences between control and treatment groups, a score was calculated. Participants in the treatment group performed all three behaviours more often (92%, n = 33) than participants in the control group (67%, n = 18). A Fisher's Exact Test was conducted on the frequencies for a two-sided alternative hypothesis, indicating that there were significant differences between the groups ($p < 0.05$).

Observational data also showed that more participants from the treatment group (100%) scanned to the right as compared to participants from the control group (85%). A Fisher's Exact Test was

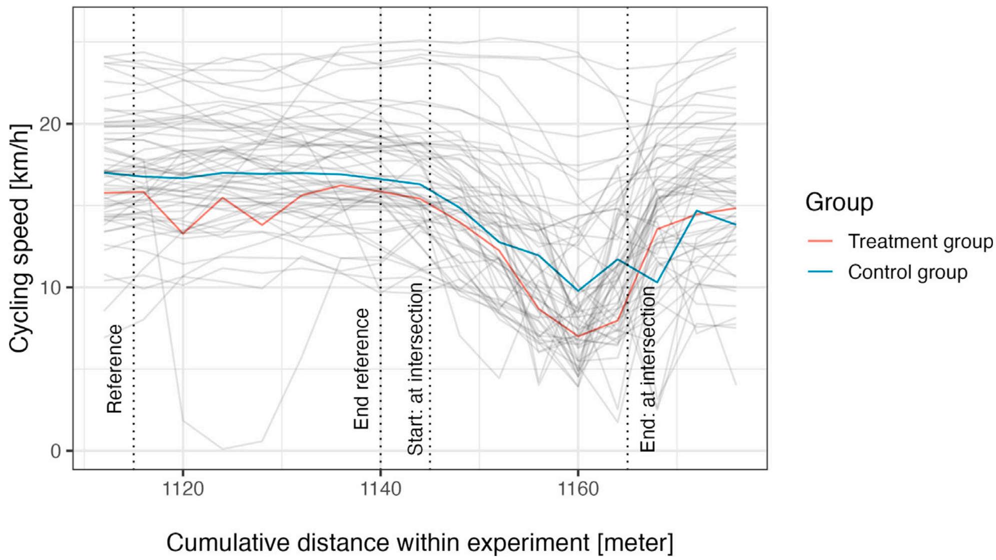


Fig. 7. Evaluation right-of-way: cycling speed prior intersection, at intersection and after intersection. Grey lines represent individual participants' cycling speeds.

conducted on the frequencies for a two-sided alternative hypothesis, indicating that there were significant differences between the groups ($p < 0.05$).

The questionnaire showed that the participants in the treatment group were more inclined to reduce their speed, with 78% of the participants stating that they would continue without pedalling, versus 40% in the control group. A Fisher's Exact Test was conducted on the frequencies for a two-sided alternative hypothesis, indicating that there were significant differences between the groups ($p < 0.05$). No significant differences between the treatment and control groups could be observed for 'scanning to the right' and 'brake readiness'.

At the intersection with a vehicle coming from the left without right-of-way, no differences between the treatment and control groups could be identified in the VR data; both groups reduced their speed prior to the intersection. More participants from the treatment group (67%) came to a full stop as compared to participants from the control group (48%). Pearson's Chi-squared test was conducted, and the results did not demonstrate a statistically significant association ($\chi^2(2) = 1.49$, $p = 0.223$).

Turning left. When making left turns at intersections, cyclists are advised to merge into the vehicle lane. Before doing so, it is recommended that they check over their shoulder, signal their intent, and ensure there is no oncoming traffic before proceeding.

Analysis of the VR data was not further pursued, due to the fact that participants had difficulties following the expected trajectory.

Observation of behaviour, with a focus on the actions of shoulder checking, signalling, and lateral positioning, did not show any significant differences between the groups.

The questionnaire did reveal a significant difference in the frequency of individuals either waiting in the left-most position or continuing and waiting for a gap in opposing traffic between the treatment (94%, n = 34) and control groups (74%, n = 20). A Fisher's Exact Test was conducted on the frequencies for a two-sided alternative hypothesis, indicating that there were significant differences between the groups ($p < 0.05$).

4.2.3. Summary

Table 9 provides a summary of the findings for each situation in both the treatment and control groups. The findings indicate differences between the groups across different situations, as assessed through VR data, observation, and questionnaire responses.

5. Discussion

5.1. Discussion of results and contribution to existing literature

The purpose of this study was to investigate the effectiveness of online cycling training on cycling skills. The impact of a specifically designed online cycling training was measured using a mixed-methods approach. Self-reported and knowledge-based skills were measured using a self-report approach as part of the online training. The impact on objective skills was examined using behavioural data collected from a VR-bicycle simulator study. Overall, the study shows that online cycling training improves cycling skills across several dimensions: self-reported skills, knowledge-based skills, and skills measured at the behavioural level.

Self-reported skills. Results indicate that the completion of online cycling training is associated with an improvement of self-reported skills, in particular for participants who cycle less frequently. This observation partially aligns with Hypothesis 1, which asserts a broad positive influence on self-reported skills. An effect for the entire population on self-reported skills was found for three out of four measured self-reported skills (i.e. predicting traffic situations, showing consideration,knowledge of how to act); notably, this effect is quite small. Greater effects were found for participants who cycle less frequently. This group assessed their ability to recognise hazards, predict traffic situations, and knowledge of how to act to be greater after completion of online training. An explanation for these findings is that participants – in particular participants who cycle more frequently – indicated high levels of self-reported cycling skills as a base line. As a result, the intervention had only limited potential to be effective, leading to a ceiling effect. Beyond that, the generally minor impact on self-reported skills could be attributed to the presence of an optimism bias. A common observation in numerous studies on self-reported driving skills is that drivers – as in other areas of behaviour – tend to be poor in evaluating their own skills, often displaying an inclination to overestimate themselves (Sundström, 2008).

Despite these considerations, the findings on the impact of online training on self-reported skills contribute to existing knowledge by providing empirical evidence of the effectiveness of such a training, particularly on self-reported cycling skills as conceptualised by de Winter et al. (2019). Furthermore, relevant conclusions can be drawn

Table 9
Summary of findings in VR evaluation study.

Training		Results depending on data sources		
Situations	Trained skills Expected effects	VR data	Observational data	Questionnaire
Lateral position with parked cars	Increased distance to parked cars	Confirmed effect	N/A	No significant effect
Roundabout	(a) Riding in centre of lance	No significant effect	N/A	Confirmed effect
	(b) Specific maneouvres (shoulder-check, signalling when entering and exiting round-about	N/A	Confirmed effect	N/A
Recognising blind spots	Halting behind truck	Confirmed effect	Confirmed effect	Confirmed effect
Right-of-way; car from the right	(a) Reducing speed	Confirmed effect	N/A	Confirmed effect
	(b) Come to a halt/give right of way	Confirmed effect	Confirmed effect	N/A
	(c) Score of specific maneouvres (finger on the brake, stopping with pedalling and active braking)	N/A	Confirmed effect	No effect (for breaking readiness)
	d) Scanning to the right	N/A	Confirmed effect	No effect
Turning left	(a) Waiting position to the most-left	N/A	No effect	Confirmed effect
	(b) Scanning to the right	N/A	No effect	N/A
	(c) Signalling	N/A	No effect	N/A

from these findings. First, online cycling training should be specifically designed and promoted for target groups who cycle less frequently. This is particularly relevant when understanding that the training generally attracted more participants who already cycle frequently. If groups of more frequent cyclists are targeted, more elaborate skills, or other types of skills (i.e. skills that relate to higher order skills such as motives or riding goals, (Lajunen and Summala, 1995)) should be trained. Second, the most significant effect of the training was found for the additionally included item, "feeling comfortable while riding a bicycle in urban traffic". This is a promising result for the promotion of cycling in general, indicating that training skills might be an important and necessary prerequisite to motivate particularly people who ride less frequently to use this healthy and environmentally friendly means of transportation.

Knowledge-based skills. A *second* important finding is that participation in online training positively impacts knowledge-based skills over time; participants are able to better identify safe behaviour after completion of online cycling training. This finding is in line with Hypothesis 2, as well as with previous research on the effectiveness of road safety education (Assailly, 2017), demonstrating an effect on a cognitive level. Beyond that, the present study contributes to the existing safety research in the context of cycling (Richmond et al., 2013), offering empirical proof of the impact of training on developing knowledge-based skill among adults. Finally, these findings are in line with the small body of literature which evaluates the usage of digital channels for road safety education (Lehtonen et al., 2017a; Kovácsová et al., 2020).

It is important to note some key considerations. Skill improvement varies depending on the type of skill trained; for some skills, the present study finds only small improvements due to an already high baseline (e.g. "right-of-way on curved priority roads" or "right-of-way at unsignalised intersections". For other skills (e.g. "performing left turns" or "awareness of blind spots"), the learning curve is very steep at the beginning, and improvements over time are non-existent or very small. A remarkable result is that the positive impact of the training on skills related to traversing roundabouts was limited to 70% of the participants. This meant that, even after completing the training, 30% of the participants still did not know how to traverse a roundabout in a safe way. This might be related to this specific type of situational skill; Some people may not believe that it is actually safer to ride in the middle of the street in a roundabout.

Notwithstanding these considerations, the study provides evidence that online training effectively improves situational skills among cyclists. However, for a practical application, situational skills must be chosen carefully to (1) ensure a potential for learning (i.e. detecting skills with a knowledge-gap) and (2) train skills in a way perceived as correct by the target group, or otherwise provide evidence that such skills are required. Alternatively, a more elaborate cycling training could also segment cyclists based on their skills or safety concerns, and train more personalised skills in accordance with these individual characteristics.

Behavioural level. Finally, the study had most impact at the behavioural level. Most notably, we found that cyclists who participated in the online training were able to recognise blind-spot situations, as measured by their cycling behaviour. Furthermore, they anticipated right-of-way situations by reducing cycling speed and yielding for traffic with priority. Also, we found that cyclists who participate in the online training maintain more distance from parked cars. However, it should be noted that, in this specific case, the differences between the treatment and control group are small. As such, these findings only partially align with Hypothesis 3, which states that an online cycling training improves cyclists' safe riding behaviour. In this way, the present study fills a gap in literature, providing partial empirical evidence for the impact of online training on actual cycling behaviour for specific skills. On a behavioural level, the study finds no impact from the online training on the correct position in roundabouts and on performing left turns.

However, direct measurement of whether cyclists who participated in the online training have a better awareness of situations was not possible. Instead, these effects were assessed by means of a follow-up questionnaire as part of the training evaluation. Results provide evidence that cyclists who participated in the training have a better understanding of their expected lane position in roundabouts and when turning left. Furthermore, the follow-up questionnaire shows that all participants are able to recognise right-of-way situations; cyclists who participated in the training are able to translate this knowledge into actual safe cycling behaviour.

Another explanation for the fact that no effects could be measured in several situations is that measuring specific manoeuvres – such as performing left turns – using a VR-bicycle simulator poses a challenge. Performing left turns on a VR-bicycle simulator requires different balancing skills than real-life cycling because the simulator is mounted on a stand, making it impossible to use body movement for turning. Users who attempt to rely on body movement instead of the steering wheel often experience a loss of balance, or a sense of imbalance. Notably, the study fails to provide effects exactly in those two situations related to turning. Observational protocol inspection revealed that a large number of participants had problems with handling the bicycle (i.e. losing control of the turning manoeuvre). Thus, the fact that no effect of the intervention (training) could be measured might be attributed to differences between cycling in a VR bicycle simulator and real-life cycling.

5.2. Limitations and future research

Online training focused on skills required to navigate safety through urban traffic. At the same time, research has shown that hazardous situations also arise due to risk-taking, especially among young adolescents (Twisk et al., 2015; O'Hern et al., 2020), and that risky behaviour decreases with age and cycling frequency (O'Hern et al., 2020). Given the crowd-sourced nature of the study, we refrained from extensively surveying attitudes, i.e. towards risky cycling behaviour. Nevertheless, we recommend that future research should include the measurement of attitudes, as well as specific training modules that address risky cycling behaviour.

Again, due to the crowd-sourced nature of the study and experiences from pre-tests, repetition of questions and/or skills required in certain situations was avoided. This lack of repetition does not allow for statistical inference of learning improvement for all trained situations within the online training. We recommend further evaluation of incorporating more repetition in an online training program. This repetition could also be limited to a specific group of cyclists, such as those who cycle less frequently.

The training evaluation was conducted using a virtual reality cycling simulator in combination with a head-mounted display. While cycling simulators have been employed for a range of purposes, including, but not limited to, VR-based learning, infrastructure evaluation and perception of safety, the performance of certain manoeuvres proved challenging, especially if these manoeuvres required hand signals, changing the lateral position and scanning to the left and right almost simultaneously.

Furthermore, the utilised simulator is not validated against real-life situations. A validation study could look into the actual and relative validity of certain measures, such as lateral position, choice of speed, and speed reduction at intersections.

A naturalistic study to evaluate the effectiveness of online training could overcome these issues. In such a study, situations can be included similar to those trained in the training program. A real-life environment provides participants with the opportunity to bicycle in urban traffic without being hindered by technology. Despite the lack of full control in a naturalistic study, it can offer valuable insights into the effectiveness of online training compared to other types of training or no training at all. Despite the lack of full control in such a naturalistic study, such a study could provide further insights in the effectiveness of an online training versus other types of training or no training.

An additional limitation of the study concerns its experimental design. Given its practical character, participants for the control group were recruited from the same population, but using different procedures as the treatment group. Thus, these procedures do not comply with the requirements of a true experiment that randomly assigns participants to treatment and control groups (randomised control trials). Instead, this study tried to determine the influence of specific sample characteristics (e.g. cycling frequency, age, and gender). While the procedures of this real-life intervention have the advantage of providing more external validity, it is important to acknowledge the limitations of the current study in terms of determining other potential confounding variables. Future investigations into the effectiveness of a training program using randomised controlled trial (RCT) methodologies might provide even more robust evidence on the causal impact of training programs on behaviour.

6. Conclusion

The current investigation provides empirical evidence for the effectiveness of online training to improve cyclists' self-reported and knowledge-based skills. Moreover, through a training evaluation employing a cycling simulator, involving both treatment and control groups, it was found that participants in the online training exhibited safer navigation in urban traffic in three out of five assessed scenarios. From a practical viewpoint, these findings bolster efforts by agencies and road safety programs to engage and train their audience through digital channels, thereby reaching a larger audience as compared to the more conventional in-situ training. Despite these positive results, performing certain manoeuvres during the training evaluation proved to be challenging. To this end, it is recommended that a field study be conducted to evaluate cycling behaviour in an even more naturalistic setting. Also, expansion of online training to address risky cycling behaviour as a further mechanism to prevent accidents is recommended. These findings, along with further research, can serve as the basis for a broader launch of an online cycling training program.

CRediT authorship contribution statement

Michael A.B. van Eggermond: Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Dorothea Schaffner:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Nora Studer:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis. **Leah Knecht:** Writing – review & editing, Investigation, Formal analysis. **Lucy Johnson:** Investigation.

Declaration of competing interest

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Appendix. Measures virtual reality study

Data availability

Data will be made available on request.

Table A.10
Measures in virtual reality study.

Scenario	Measure	Variable
Scenario 1: Maintaining distance from parked cars	Structured observation	Brake readiness
	Sensor data	Lateral position
		Speed
	Questionnaire	Looking ahead
		View direction
		Brake readiness
		Position
Scenario 2: Traversing roundabouts	Structured observation	Shoulder check
		Signalling
	Sensor data	Trigger points
		Lateral position
	Questionnaire	Position
Scenario 3: Awareness of blind spots	Structured observation	Stopping position
	Sensor data	Stopping position with trigger points
	Questionnaire	Stopping position
Scenario 4: Right-of-way at unsignalised intersections (car from right)	Structured observation	Brake readiness
		View direction to right
		Give right of way
	Sensor data	Trigger point
		Speed
	Questionnaire	Looking ahead
		View direction
		Brake readiness
		Signalling
		Speed
Scenario 5: Right-of-way at unsignalised intersections (car from left)	Structured observation	Brake readiness
	Sensor data	Trigger point
		Speed
	Questionnaire	Looking ahead
		View direction
		Brake readiness
		Signalling
		Speed
Scenario 6: Performing left turns	Structured observation	Shoulder check
		Signalling
		Position
	Sensor data	–
	Questionnaire	Position

References

Ābele, L., Haustein, S., Mø ller, M., Martinussen, L.M., 2018. Consistency between subjectively and objectively measured hazard perception skills among Young male drivers. Accid. Anal. Prev. 118, 214–220. http://dx.doi.org/10.1016/j.aap.2018.02.022.

Assailly, J.P., 2017. Road safety education: What works? Patient Educ. Couns. 100, 24–29. http://dx.doi.org/10.1016/j.pec.2015.10.017.

bfu, 2021. Regelmissachtungen im Veloverkehr. Technical Report, bfu, p. 20.

Chand, C., Jashami, H., Scott-Deeter, L., Koonce, P., Hurwitz, D., 2024. Evaluation of door zone conflicts between bicycles and parked vehicles. Transp. Res. Rec. http://dx.doi.org/10.1177/03611981241242760.

Colwell, J., Culverwell, A., 2002. An examination of the relationship between cycle training, cycle accidents, attitudes and cycling behaviour among children. Ergonomics 45 (9), 640–648. http://dx.doi.org/10.1080/00140130210156303.

de Winter, J.C.F., Kovácsová, N., Hagenzieker, M.P., 2019. Cycling Skill Inventory: Assessment of motor–tactical skills and safety motives. Traffic Inj. Prev. 20 (sup3), 3–9. http://dx.doi.org/10.1080/15389588.2019.1639158.

Dill, J., McNeil, N., 2013. Four types of cyclists? Examination of typology for better understanding of bicycling behavior and potential. Transp. Res. Rec. 2387, 129–138. http://dx.doi.org/10.3141/2387-15.

Ducheyne, F., De Bourdeaudhuij, I., Lenoir, M., Cardon, G., 2013. Does a cycle training course improve cycling skills in children? Accid. Anal. Prev. 59, 38–45. http://dx.doi.org/10.1016/j.aap.2013.05.018.

Elander, J., West, R., French, D., 1993. Behavioral correlates of individual differences in road-traffic crash risk: An examination of methods and findings. Psychol. Bull. 113 (2), 279–294. http://dx.doi.org/10.1037/0033-2909.113.2.279.

Endsley, M.R., 1995. Toward a theory of situation awareness in dynamic systems. Hum. Factors J. Hum. Factors Ergon. Soc. 37 (1), 32–64. http://dx.doi.org/10.1518/001872095779049543.

European Commission, 2021. Facts and Figures Cyclists. European Road Safety Observatory. Technical Report, European Commission, Directorate General for Transport, Brussels.

Faus, M., Alonso, F., Esteban, C., Useche, S., 2022. Are adult driver education programs effective? A systematic review of evaluations of accident prevention training courses. Int. J. Educ. Psychol. http://dx.doi.org/10.17583/ijep.8805.

Gálvez-Fernández, P., Chillón, P., Aranda-Balboa, M.J., Herrador-Colmenero, M., 2022. Preliminary results of a bicycle training course on adults' environmental perceptions and their mode of commuting. Int. J. Environ. Res. Public Health 19 (6), 3448. http://dx.doi.org/10.3390/ijerph19063448.

Golding, J.F., 2006. Predicting individual differences in motion sickness susceptibility by questionnaire. Pers. Individ. Differ. 41 (2), 237–248. http://dx.doi.org/10.1016/j.paid.2006.01.012.

Haasnoot, J., Happee, R., van der Wijk, V., Schwab, A.L., 2023. Validation of a novel bicycle simulator with realistic lateral and roll motion. Veh. Syst. Dyn. 62 (7), 1802–1826. http://dx.doi.org/10.1080/00423114.2023.2264418.

Hamari, J., Koivisto, J., Sarsa, H., 2014. Does gamification work? – A literature review of empirical studies on gamification. In: 2014 47th Hawaii International Conference on System Sciences. pp. 3025–3034. http://dx.doi.org/10.1109/HICSS.2014.377.

Hatakka, M., Keskinen, E., Gregersen, N.P., Glad, A., Hernetkoski, K., 2002. From control of the vehicle to personal self-control; broadening the perspectives to driver education. Transp. Res. F 5 (3), 201–215. http://dx.doi.org/10.1016/S1369-8478(02)00018-9.

Hatfield, J., Boufous, S., Eveston, T., 2019. An evaluation of the effects of an innovative school-based cycling education program on safety and participation. Accid. Anal. Prev. 127, 52–60. http://dx.doi.org/10.1016/j.aap.2019.02.021.

Kaptein, N.A., Theeuwes, J., van der Horst, R., 1996. Driving simulator validity: Some considerations. Transportation Research Record: Journal of the Transportation Research Board 1550 (1), 30–36. http://dx.doi.org/10.1177/0361198196155000105.

Keler, A., Kaths, J., Chucholowski, F., Chucholowski, M., Grigoropoulos, G., Spangler, M., Kaths, H., Busch, F., 2018. A bicycle simulator for experiencing microscopic traffic flow simulation in urban environments. In: 2018 21st International Conference on Intelligent Transportation Systems. IEEE, Maui, HI, pp. 3020–3023. http://dx.doi.org/10.1109/ITSC.2018.8569576.

Kovácsová, N., Vlakveld, W.P., de Winter, J., Hagenzieker, M., 2020. PC-based hazard anticipation training for experienced cyclists: Design and evaluation. Saf. Sci. 123, 104561. http://dx.doi.org/10.1016/j.ssci.2019.104561.

Kronqvist, A., Jokinen, J., Rousi, R., 2016. Evaluating the authenticity of virtual environments: Comparison of three devices. Adv. Hum.-Comput. Interact. 2016, 1–14. http://dx.doi.org/10.1155/2016/2937632.

Lajunen, T., Summala, H., 1995. Driving experience, personality, and skill and safety-motive dimensions in drivers' self-assessments. Pers. Individ. Differ. 19 (3), 307–318. http://dx.doi.org/10.1016/0191-8869(95)00068-H.

Larsen, J., 2017. The making of a pro-cycling city: Social practices and bicycle mobilities. Environ. Plan. A Econ. Space 49 (4), 876–892. http://dx.doi.org/10.1177/0308518X16682732.

Lehtonen, E., Airaksinen, J., Kanerva, K., Rissanen, A., Ränninranta, R., Åberg, V., 2017a. Game-based situation awareness training for child and adult cyclists. Royal Soc. Open Sci. 4 (3), 160823. http://dx.doi.org/10.1098/rsos.160823.

Lehtonen, E., Sahlberg, H., Rovamo, E., Summala, H., 2017b. Learning game for training child bicyclists' situation awareness. Accid. Anal. Prev. 105, 72–83. http://dx.doi.org/10.1016/j.aap.2016.07.036.

Macarthur, C., Parkin, P.C., Sidky, M., Wallace, W., 1998. Evaluation of a bicycle skills training program for Young children: A randomized controlled trial. Inj. Prev. 4 (2), 116–121. http://dx.doi.org/10.1136/ip.4.2.116.

Mandic, S., Flaherty, C., Pocock, T., Kek, C.C., McArthur, S., Ergler, C., Chillón, P., Bengoechea, E.G., 2018. Effects of cycle skills training on children's cycling-related knowledge, confidence and behaviours. J. Transp. Health 8, 271–282. http://dx.doi.org/10.1016/j.jth.2017.12.010.

McLaughlin, K.A., Glang, A., 2010. The effectiveness of a bicycle safety program for improving safety-related knowledge and behavior in Young elementary students. J. Pediatr. Psychol. 35 (4), 343–353. http://dx.doi.org/10.1093/jpepsy/jsp076.

Nazemi, M., van Eggermond, M.A.B., Erath, A., Axhausen, K.W., 2019. Studying cyclists' behavior in a non-naturalistic experiment utilizing cycling simulator with immersive virtual reality. In: Annual Meeting of the Transportation Research Board. Washington, D. C..

Nazemi, M., van Eggermond, M.A.B., Erath, A., Schaffner, D., Joos, M., Axhausen, K.W., 2021. Studying bicyclists' perceived level of safety using a bicycle simulator combined with immersive virtual reality. Accid. Anal. Prev. 151, 105943. http://dx.doi.org/10.1016/j.aap.2020.105943.

O'Hern, S., Oxley, J., Stevenson, M., 2017. Validation of a bicycle simulator for road safety research. Accid. Anal. Prev. 100, 53–58. http://dx.doi.org/10.1016/j.aap.2017.01.002.

O'Hern, S., Stephens, A.N., Young, K.L., Koppel, S., 2020. Personality traits as predictors of cyclist behaviour. Accid. Anal. Prev. 145, 105704. http://dx.doi.org/10.1016/j.aap.2020.105704.

Richmond, S.A., Zhang, Y.J., Stover, A., Howard, A., Macarthur, C., 2013. Prevention of bicycle-related injuries in children and youth: A systematic review of bicycle skills training interventions. Inj. Prev. 20 (3), 191–195. http://dx.doi.org/10.1136/injuryprev-2013-040933.

ROSE 25 EU, 2005. Inventory and Compiling of a European Good Practice Guide on Road Safety Education Targeted at Young People, TI. Technical Report TREN/E3/47-2003 SER-B27020B-E3-2003-Good Practices-S07.28326.

Savill, T., Bryan-Brown, K., Harland, G., 1996. The Effectiveness of Child Cycle Training Schemes. Technical Report TRL214, Transport Research Laboratory.

Sundström, A., 2008. Self-assessment of driving skill – A review from a measurement perspective. Transp. Res. F 11 (1), 1–9. http://dx.doi.org/10.1016/j.trf.2007.05.002.

Twisk, D.A.M., Commandeur, J.J.F., Vlakveld, W.P., Shope, J.T., Kok, G., 2015. Relationships amongst psychological determinants, risk behaviour, and road crashes of Young adolescent pedestrians and cyclists: Implications for road safety education programmes. Transp. Res. F 30, 45–56. http://dx.doi.org/10.1016/j.trf.2015.01.011.

van Eggermond, M.A.B., Schaffner, D., Studer, N., 2022. Assessing cycling skills in Switzerland. In: International Cycling Safety Conference. Dresden.

van Eggermond, M.A.B., Schaffner, D., Studer, N., 2023. Sicher Und Kompetent Unterwegs: Eine Analyse Zu Velofahrkompetenzen Und Unfallprävention. Strasse Verkehr 1–2 (2023).

Wallius, E., Klock, A.C.T., Hamari, J., 2022. Playing it safe: A literature review and research agenda on motivational technologies in transportation safety. Reliab. Eng. Syst. Saf. 223, 108514. http://dx.doi.org/10.1016/j.ress.2022.108514.

WIVW, 2024. Würzburger Institut Für Verkehrswissenschaften GmbH.