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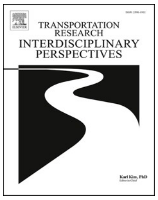

Improving children's on-road cycling with immersive video-based training: A pilot study

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ABSTRACT

Cyclists are frequent casualties in road traffic collisions, and cyclist inattention is often implicated. Children are more distractible than adults and so are arguably more vulnerable road users, including when cycling. Research shows that misallocation of attention or distraction is a common factor in crashes involving cyclists, and child cyclists are more likely to be seriously injured, possibly because their hazard perception is inferior to that of adults. Video-based training paradigms designed to improve children's hazard perception and situation awareness have yielded mixed findings, but none have examined positive transfer of such training interventions to on-road cycling performance. The aim of this study was to use an immersive video-based training protocol to improve attention allocation, situation awareness and on-road cycling performance in children who had completed UK cycle training aimed at 9–11-year-olds. Thirty-three children aged 10–12 years were randomly allocated to either an Intervention group or a Control group. All participants reported their cycling behaviour and cycling self-efficacy, and completed online situation awareness tests at baseline, post-test, and retention stages. Between baseline and post-test, the intervention group ($n = 17$) completed a lab-based training protocol in which they viewed real-world cyclist point-of-view footage on an immersive screen while pedalling on a stationary cycle. As they navigated five virtual routes their task was to demonstrate awareness of potential hazards and other information pertinent to their safety, with decreasing levels of support from the researcher as they progressed. The control group did not receive the training intervention. All participants' cycling performance was individually assessed on urban roads on two testing occasions, by qualified cycle instructors. The intervention group outperformed the control group in terms of their on-road performance, in terms of *Making good and frequent observations* (Observation; $F[1,31]) = 16.53$, $\eta_p^2 = 0.35$, $p = 0.0003$,); *Communicating intentions clearly to others* (Communication; $F[1,31]) = 13.70$, $\eta_p^2 = 0.31$, $p = 0.001$); *Choosing and maintaining the most suitable riding positions* (Position; $F[1,31]) = 7.41$, $\eta_p^2 = 0.19$, $p = 0.01$); and *Understanding priorities on the road, particularly at junctions* (Priorities; $F[1,31]) = 6.88$, $\eta_p^2 = 0.18$, $p = 0.01$), although this was not accompanied by significant changes in their cycling self-efficacy and situation awareness, all p's > 0.05. The present findings suggest that an immersive video-based protocol such as the one herein may improve children's safety when cycling on roads and may therefore be an effective complement to current cycle training protocols. Given ongoing governmental investment in cycling infrastructure in the UK, with a concomitant increase in micromobility modes of active travel, national policy will need to consider the additional perceptual-cognitive demands that will face young cyclists; immersive training is a potentially efficient and cost-effective way to mitigate these demands. However, further research attention should be devoted to the development of effective situation awareness tests – preferably ones that correlate with, if not predict, children's independent on-road cycling performance.

Introduction

Cyclists are frequent casualties in road traffic collisions (Björnstig et al., 2017; Isaksson-Hellman & Werneke, 2017). In Great Britain, an average of 20 cycle trips per person were made in 2019, compared to an average of 295 trips made by drivers of cars and vans in the same year – a

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ratio of approximately 1 to 15. In contrast, of the 36,563 road user casualties reported in the same year, 3,360 of those were cyclists – a ratio of approximately 1 to 11; this casualty rate is exceeded only by motorcyclists. Human error was the main contributor to these incidents – particularly road users' failure to "look properly" at junctions (DfT, 2020). Consistent with these national statistics, empirical investigations of collisions and near-misses involving cyclists frequently implicate road users' misallocation of attention or distraction (Møller et al., 2021; Salmon et al., 2022; Stimpson et al., 2013; Terzano, 2013; Tuckel et al., 2014; Useche et al., 2018), and some data show that child cyclists are more likely to be serious casualties than adults (Nicaj et al., 2009), possibly because of children's inferior impoverished ability to detect looking hazards relative to adults (Wann et al., 2011). Vanparijs and colleagues (2016) analysed bicycle crash data comprising observational and self-report data obtained from Belgian insurance companies (n = 77) and schools (n = 86), for children aged 14–18 years of age. Of the six main causes they identified, the two most prevalent were cyclist distraction and other road users' failure to see cyclists. Therefore, there is a need to investigate ways in which children's cycle safety can be enhanced, with a specific focus on improving their allocation of attention, hazard perception and situation awareness when cycling.

The Bikeability Trust is the national charity for the UK government's cycle education programme and has trained >3.6 million children since its inception in 2007. It currently provides training for approximately 420,000 children in England per year. This training requires children to demonstrate their ability to cycle on urban roads in accordance with four Core Functions laid out in the UK National Standard for cycle training (DfT & DVSA, 2019), namely: *Making good and frequent observations* (hereafter 'Observation'); *Communicating intentions clearly to others* (Communication); *Choosing and maintaining the most suitable riding positions* (Position); and *Understanding priorities on the road, particularly at junctions* (Priorities). The Bikeability Delivery Guide (2022), states that "Riders should progress by identifying and responding to a wide range of hazards encountered in increasingly challenging cycling environments and demonstrating a deeper understanding of how effective hazard perception and response to hazards underpin safe and responsible cycling strategies." However, when completing Bikeability Level 2 training, children's ability to look properly, to make good and frequent observations and to identify hazards are not explicitly trained or assessed.

Nonetheless, there is evidence to suggests that Bikeability Level 2 training is effective. In a longitudinal study, Hodgson and Worth (2015) asked 10–11-year-olds who had completed Bikeability Level 2 training to complete a screen-based assessment of their hazard perception ability, 1–3 weeks after training and approximately-two months later. They outperformed a comparator group of the same age who had not completed the training. However, whilst effect sizes were large, the effect of the training waned between the two assessment points. This may reflect the children's self-reported cycling frequency, as there were no between-group differences on this measure in a post-study evaluation. However, this lack of difference may reflect social inequalities: Even though Bikeability training is inclusive in its scope, approximately 30 % of UK 11-year-olds do not have access to a pedal cycle, and less than half of all adults have access to a cycle (Department for Transport, 2021) – many of whom are parents. Immersive cycle training that does not require cycle ownership could be a viable means of circumventing this barrier, thereby maintaining, or even improving, children's hazard perception skills after Bikeability Level 2 training completion.

Hazard perception is underpinned by effective looking behaviour, which can be determined by a combination of gaze behaviour (e.g., Kovácsová et al., 2018) and head movements (e.g., Bogacz et al., 2020; O'Hern et al., 2017). Gaze behaviour can be characterised by various metrics including the number of fixations made on an area of interest (AOI) and the amount of time spent looking at an AOI (i.e., dwell times). These metrics provide a useful index of both visual attention and perceptual expertise: Skilled performers in a variety of domains typically scan their visual environment more efficiently and pick up more relevant information when they fixate their gaze (Gegenfurtner et al., 2011; Gredin et al., 2018; Mann et al., 2007), and this advantage may include differences between adult and child cyclists. Vansteenkiste et al. (2017) asked 18 adults and 16 children to cycle along cycle tracks that varied in their quality (see also Vansteenkiste et al., 2014). Although the two group's fixation durations and gaze distribution patterns were similar, the adults fixated on the track surface ahead more frequently, whereas the children tended to fixate on task-irrelevant locations more often; this may reflect children's relatively high distractability compared to adults (Nice, 2018). It is important to explore ways in which children can be trained to fixate more often on task-relevant locations when cycling.

Effective head turning is also a marker of expertise in dynamic real-world contexts (McGuckian et al., 2019; Rojas Ferrer et al., 2020). However, examinations of road users' head movements have typically been observational studies of inattention and traffic violations at junctions, using remote cameras to detect those movements (e.g., Fraboni et al., 2018; Rasanen & Summala, 1998; Summala et al., 1996; Wolfe et al., 2016). A recent exception is a study by Bogacz and colleagues (2020), who compared the cycling behaviour of two groups of participants in an immersive cycling setup. One group of participants controlled a virtual cycle using a traditional keyboard whilst another group rode an instrumented bicycle to do so. The latter group made head movements that were like those they would make in the real world. Such *representative task design* is an important consideration for experimental studies, if we are to mimic real-world perceptual and attentional process (Dicks et al., 2009). Moreover, head movements can easily be observed during on-road assessments, without recourse to specialist equipment.

The designs of hazard perception tests are varied (Moran et al., 2019), although most cycling-based ones comprise naturalistic stimuli depicting point-of-view (POV) video footage obtained from a bicycle-mounted camera (e.g., Castro et al., 2020; de Geus et al., 2020; Vansteenkiste et al., 2016). Using these tests, cyclists' gaze behaviour has been investigated experimentally. For example, Kovácsová and colleagues (2018) used a laboratory protocol to investigate cyclists' eye movements as they navigated a variety of virtual intersections; car approach scenario, traffic complexity and cycling speed were manipulated. Cycling speed did not have a large effect on the cyclists' eye movements or crossing judgements, but increased traffic complexity led to greater scanning of the environment – although their attention was predominantly directed to cars that posed a more immediate threat (cf. Frings et al., 2014; Rasanen & Summala, 1998). Relatedly, inexperienced cyclists look around more at junctions than experienced cyclists, whose gaze is more fixated on relevant information (Rupi & Krizek, 2019).

Comparisons of children's and adults' performance on video-based tests suggests that children's hazard perception may be inferior. For example, using a video-based hazard perception test comprising cyclist POV footage, Zeuwts et al. (2017a) compared young cyclists' and adult cyclists' performance. The children reacted more slowly to hazards, which was manifested in slower time to first fixate on latent covert hazards – i.e., those that were initially or partially hidden from view. Relatedly, Melin et al. (2018) showed that even inexperienced adult cyclists identified more hazards than did children – especially so for vulnerable roads users such as cyclists. De Geus, Vlakveld, and Twisk (2020) also used a video-based task comprising cycling POV footage to examine 12–14-year-olds' hazard detection performance relative to that of adults aged 19 to 62 years; they monitored all participants' eye movements as they completed the task. Whilst the adults' decision-making performance was superior – they also perceived greater danger in hazardous situations – there were no differences in the two groups' detection of hazards or gaze behaviour. Moreover, when performing the task in the presence of a distracting peer, both children and adults spent less time fixating on task-relevant regions of the visual display than they did in a control condition without distraction. Hence, both groups may benefit from being trained to allocate their visual attention more effectively, not least in the context of environmental distractions.

Whilst gaze behaviour is an important marker of visual attention, we must also acknowledge that we can look directly at something yet not perceive it, because our covert attention is directed elsewhere – what has been termed *inattentional blindness* (Simons & Chabris, 1999). Consequently, to better understand cyclists' attention allocation, it is important to assess their situation awareness; namely, their *perception* of elements within time and space, their *comprehension* of the meaning of those elements, and their *projection* of their future state (Endsley, 1995). Situation awareness has been investigated extensively in driving (e.g., Baumann & Krems, 2007; Endsley, 2020; Gugerty, 2011; Underwood et al., 2013) and more recently in cycling (e.g., Beanland & Hansen, 2017; Lehtonen et al., 2017b). Several authors have made a distinction between situation awareness and hazard perception and the associated testing processes (e.g., Horswill & McKenna, 2004; Jackson et al., 2009; Lehtonen et al., 2017a; Salmon et al., 2012). These distinctions encompass the notion that hazard perception tests comprise an overt response to a perceived hazard (e.g., a button press). However, situation awareness tests also assess road users' awareness of various elements of a situation that may not be hazardous but could influence the extent and severity of hazards. For example, assessment of a cyclist's situation awareness may include their *perception* of an impending speed limit increase (e.g., from viewing a speed limit sign), their understanding of what this could mean in terms of the extent and severity of potential hazards (*comprehension*), then their anticipation of what they may need to do further ahead on their route to navigate safely (*projection*). The speed limit increase is not a hazard as such, but it could change the speed and volume of motor traffic that a cyclist encounters – which arguably makes traffic scenarios more hazardous.

There is some evidence that children's situation awareness when cycling is inferior to that of adults. Vansteenkiste et al. (2016) administered a video-based hazard perception test to a group of young adults and a group of children, to assess their gaze behaviour, situation awareness and risk perception. Although the adults reacted quicker to hazards, situation awareness was similar for the two groups – but adults also rated the scenarios as more hazardous (cf. De Geus et al., 2020). Hence, although children's *perception* may be comparable to that of adults, their *comprehension* may be lacking due to less real-world experience (including from driving), which consequently impairs their ability to anticipate future events (*project*). However, this may be improved with video-based training (Zeuwts et al., 2017b) – a notion that warrants further investigation.

Video-based training protocols have proven successful for retraining looking behaviour, in novices and skilled exponents, in a variety of contexts that include surgery (Vine et al., 2012), law enforcement (Heusler & Sutter; 2020), sport (D'Innocenzo et al., 2016; Broadbent et al., 2015a) and driving (Pradhan et al., 2009; Krishnan et al., 2019). Video-based hazard perception and situation awareness training programs targeted at drivers have proven similarly successful; success that has manifested not only in drivers' performance in video-based hazard perception tests, but also in their on-road driving (Horswill et al., 2022; McDonald et al., 2015; Thomas et al., 2016; For example, in a recent study, Horswill and colleagues used dashcams and GPS tracker devices to assess two groups of young drivers' on-road performance, including their braking, speeding and over-revving of their engines – behaviours related to crash risk (Horswill et al.). A training group completed six 30-minute video-based sessions to train their hazard perception skills (cf. Horswill et al., 2021) in which they were required to predict what happens next in 17 video clips comprising traffic situations, to perform crash analysis for a series of 9 clips obtained from dashcam footage of traffic crashes, provide running commentary when viewing video clips taken from a driver's perspective, and to identify where any potential traffic conflicts with other road users – i.e., situations in which the driver may need to reduce their speed or alter their course to prevent a crash. There were large effects on the trained drivers' behaviour. Specifically, their speeding, braking and engine revving were considerably lower than those of a waitlist control group. The notion that the effects of a video-based intervention could *positively transfer* to on-road performance metrics that were not explicitly developed in the intervention, also merits further scrutiny.

There is comparatively little research examining the use of video-based training protocols to develop hazard perception and situation awareness when cycling – albeit with some exceptions (e.g., Kovácsová et al., 2020; Lehtonen et al., 2017b; Zeuwts et al., 2017b; Zeuwts et al., 2018) even though this could be a safe alternative or complement to on-road training. For example, Lehtonen et al., 2017b conducted a gamified training study in which 8–9-year-olds and a comparator group of young adults viewed videos filmed from a cyclist's perspective. The participants' aim was to identify overt and covert hazards to obtain points; trial-by-trial feedback was provided for missed or late-identified hazards. A similar video-based task was used to assess the participants' situation awareness before and after the training intervention: when the footage was occluded, the participants' task was to identify locations in which they had seen hazards. The adults outperformed the children in both the gamified task and the situation awareness test. Although the children were generally quicker to respond after training, there was no change in their sensitivity to potential hazards. The authors concluded that their video-based protocol cannot be regarded as an effective tool for situation awareness/hazard perception training.

A potential explanation for the lack of a training effect in the study by Lehtonen and colleagues (2017) may be that non-representative task design constrained participants' learning. Specifically, behaviours germane to real-world cycling such as head turning were not required – despite its essentiality for safe cycling; for example, many potential hazards, such as drivers attempting to overtake them (Feng et al., 2018), are to the cyclist's rear. In many video-based training protocols, participants typically view the footage on a computer screen and respond verbally or via button press, which does not mimic the behaviour required in the real world, especially at junctions comprising 90° turns, such as *T*-junctions and crossroads. Given the cruciality of our heads for gaze control (Vickers, 2007), and for navigating both virtual and real-world junctions when cycling (O'Hern et al., 2017), exploration of alternative training methods that necessitate real-world head-turning behaviour is required. Moreover, video-based training interventions have not assessed the extent of positive transfer to actual on-road cycling performance, even though this has been done in driving (e.g., Beanland & Hansen, 2017; Horswill et al., 2022). If our aim is to enhance real-world behaviour, then we must demonstrate such benefits (Broadbent et al., 2015b).

In a recent study, Kovácsová and colleagues (2020) developed a computer-based hazard anticipation training protocol for experienced cyclists, which they delivered to a group of predominantly middle-aged and older electric bicycle users. The participants were divided into a training group ($n = 33$) and a control group ($n = 33$). All participants underwent on-screen assessment and training via a computer monitor, with a total training period of ~50 min for each group. However, whereas the control group only viewed a series of video clips relating to road user behaviour, traffic rules and situation awareness, the intervention group also received additional training to improve their knowledge of the traffic environment, experience of traffic situations, anticipation of hazards and their understanding of various traffic situations. Real-world cyclist point-of-view and aerial view footage were used to deliver these modules, and intervention participants received computerised visual and auditory feedback about their performance. Although there were no post-intervention differences in hazard detection, the training group were faster to identify hazards than their control group counterparts. The training minorly improved participants' hazard prediction accuracy at safety-critical junctions but did not change their perceptions of danger and risk in hazardous situations. But importantly, participants' evaluations of the training indicated that that the filming height of the POV footage was not representative of a cyclist's perspective, the cycling speed in the footage was too fast, and there was an absence of traffic sounds – although they liked the realism of the traffic scenarios. It would therefore represent a development of Kovácsová et al.'s work, to use filming heights and cycling speeds that represent a cyclist's perspective more faithfully, and to include ambient noise acquired during filming.

The emergence of immersive virtual reality technology has provided a promising avenue for research (Bogacz et al., 2020). Recently, van Paridon et al. (2021) developed a Cycling and Hazard Perception virtual reality simulator (CHP-VR simulator) in which cyclists could demonstrate their hazard perception skills and situation awareness in a virtual environment. Participants regularly turned their heads to look over their shoulder and monitor traffic coming from behind. However, the authors noted that participants' gaze behaviour differed from that seen in the real world, possibly because their virtual environment could not fully replicate the inherent dynamics of the real world; user embodiment is consequently limited – as are associated cognitive processes. A possible solution to this may be immersive video-based protocols that comprise real-world footage; such protocols have successfully been used to improve decision making skills in fast-paced dynamic settings (e.g., Panchuk et al., 2018). However, to our knowledge no researchers have examined the use of an immersive video-based training protocol to improve children's situation awareness and on-road cycling performance.

Aims of the present study

Given that inattention and distraction are implicated in RTAs involving child cyclists (Nicaj et al., 2009; Nikolas et al., 2016; Vanparijs et al., 2016), it is important to understand how we may improve children's ability to allocate their attention when cycling. Therefore, the primary aim of this study was to use an immersive video-based training protocol to improve looking behaviour and situation awareness in children who had completed Bikeability Level 2 training. We predicted that an immersive protocol comprising cycling POV video footage that depicts appropriate road positioning and awareness of road user priorities, which necessitates head turning and signalling behaviour similar to that required in the real world, would improve on-road cycling performance as assessed vis-à-vis the four Core Functions of *Observation*, *Communication*, *Position* and *Priorities* laid out in the UK National Standard for cycling (Department for Transport and Driver Vehicle Standards Agency, 2019).

Material and methods

Participants and study design

Thirty-three children (17 female) aged 10–12 years, all of whom had undertaken Bikeability Level 2 training in the preceding two years, volunteered to take part in this study. All of them had normal or corrected-to-normal sight and hearing, had been cycling independently for 1–6 years (*M* = 4.77 yrs; *SD* = 1.38 yrs) and cycled 0–7 times per week (*M* = 2.03; *SD* = 1.42). They self-reported ethnicities included White British/Irish (15), Indian (8), Mixed race (3), Mixed Race – White Asian (1), Asian – Other (1), Asian – Other Mixed Asian (1), Afghan/British (1), Other – Anglo-Indo (1), Other – Arab (1), and Other – White-African (1). Two participants self-identified as having autistic spectrum disorder, and one of these also had cerebral palsy.

In a mixed design, participants were randomly allocated either to an Intervention group (n = 17; 9 female) or a Control group (n = 16; 8 female) with matching: the makeup of the groups was monitored, to achieve as much parity as possible regarding the demographic characteristics listed above, including their levels of cycling experience and training. Both groups completed several baseline measures. The Intervention group then completed an immersive training session. Both groups subsequently completed post-test and retention tests that comprised both online and on-road components. A schematic of the study protocol is provided in Fig. 1.

Equipment and materials

Baseline

Each participant and a parent/carer met with the researcher online, via a mutually convenient virtual platform which enabled screen sharing (e.g., Microsoft Teams, Zoom). The device used by the participant had to have a screen comprising a minimum diagonal dimension of 9.7 in. that supported video playback via YouTube. The online platform used to collect the baseline measures was Qualtrics (Seattle, WA). Participants were required to self-report demographic information (e.g., gender, ethnicity) and cycling behaviour (e.g., the number of years for which they had cycled independently and their weekly cycling frequency), and then complete a cycling self-efficacy questionnaire and an online situation awareness test.

Cycling self-efficacy questionnaire. Self-efficacy judgments are a strong determinant of positive behavioural outcomes in a variety of contexts (e.g., physical activity; Young et al., 2014), but there is some evidence that children are overconfident in estimating their cycling proficiency (Twisk et al., 2018). Accordingly, participants were required to indicate their confidence in their ability to perform several functions when cycling on roads, at baseline, post-test, and retention. The questionnaire comprised of 16 items, relating to navigating junctions (3 items), responding to hazards (1 item) and each of the four Core Functions. Participants stated their confidence on a scale from 0 (I cannot do this at all) to 100 (I can definitely do this). An average self-efficacy score was calculated for *navigating junctions* (Item 1, 2, 3), *making good and frequent observations* (Item 4, 5, 6, 10), *communicating intentions clearly to others* (Item 11, 12), *choosing and maintaining the most suitable riding positions* (Item 8, 9), *understanding priorities on the road* (Item 13, 14, 15, 16), and *responding to hazards* (Item 7).

Online situation awareness tests. Despite longstanding discussion and validation of situation awareness tests for driving (Crundall, 2016; Salmon et al., 2012; Sirkin et al., 2017), the development of equivalent cycling-based tests is still in its infancy – especially so for online assessments; for example, there is currently no cycling counterpart for the UK driving hazard perception test. Considering this, and the ongoing restrictions of the Covid-19 pandemic, we developed a bespoke online situation awareness test comprising 20 unique video clips was presented to participants on each testing occasion (i.e., baseline, post-test, retention), in a partially counterbalanced order across participants; three different versions were used. The first, second and fourth authors independently reviewed a pool of 179 clips and assigned a challenge rating of *Low*, *Moderate* or *High* to each one. Only clips for which unanimous independent agreement was reached were selected; 76 clips remained. Video clips were distributed across the three different test versions such that each one comprised eleven low challenge clips, six moderate challenge clips and three High challenge clips; hence, 16 clips were discarded at this stage. Footage was filmed by the first author on major and minor UK roads, from a cyclist's perspective, using a 170-degree field-of-view camera (GoPro Hero 5; GoPro Inc. CA) mounted on the handlebar stem of an all-terrain bicycle; cycling speed was approximately 10 mph, and riding positions conformed to the UK National Standard for cycle training (DfT & DVSA, 2019) and the UK Highway Code. The video footage was edited in Adobe Premiere Pro (Adobe, San Jose, CA) and uploaded onto a private YouTube account so that it could be played via Qualtrics. Each video clip was occluded, without a freezeframe (cf. Crundall, 2016; Jackson et al., 2009) followed by a multiple-choice question designed to assess the *perception* and *comprehension* components of participants' situation awareness (cf. Crundall, 2016; Endsley, 1995; Endsley, 2021). Example questions include “Were

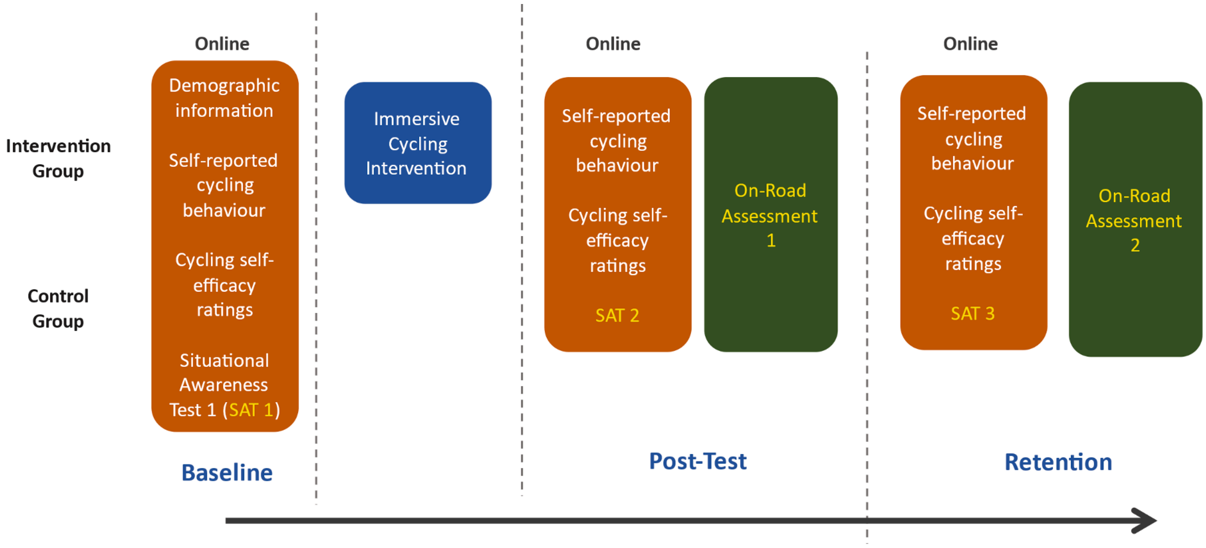


Fig. 1. Study Protocol Schematic.

there any vehicles in the side road?" (Yes/No; *Low challenge*), "What colour were the traffic lights when the video ended?" (Green or Amber or Red; *Moderate challenge*) and "How many pedestrians crossed the road ahead of you?" (0 or 1 or 2; very distal [cf. Kovácsová et al., 2020]; *High challenge*). Participants responded by selecting the answer they deemed to be correct; response formats were predominantly binary and required yes/no responses, with some exceptions, as illustrated in the examples above.

Immersive training intervention

Video acquisition. The video used in the immersive intervention was captured using an Insta360 One camera (Insta360, Irvine, CA) mounted on a strut affixed to the crossbar of a Specialized Hardrock mountain bicycle, ridden by the first author; the strut projected 30 cm in advance of the handlebar stem, such that the camera was positioned at a height of 55 in. from the ground – approximately the median height of UK 10-year-olds – to acquire a young cyclist's POV footage. Multiple routes in the London Borough of Hillingdon, UK. All routes incorporated both major and minor roads that passed nearby, or directly past, primary schools in the borough; schools attended by the participants. The researcher cycled at an average speed of approximately 10 mph, adopted riding positions in accordance with the UK National Standard for cycle training (DfT & DVSA, 2019) and always observed the UK Highway Code.

Video editing. Video footage was edited using both the Insta360 Studio app (Insta360, Irvine, CA) and the GoPro FX Reframe plugin in Adobe Premiere Pro (Adobe, San Jose, CA), to create a flattened image for further editing. A total of five immersive videos with a combined duration of 47 min and 52 s were created; video durations ranged from 6 min and 14 s (video 1) to 11 min 44 s (video 5).

A series of auditory question prompts recorded by the first author were inserted into each of the first four intervention videos at points relating to events and potential hazards in those videos, to promote participants' situation awareness; example prompts include "Did the oncoming vehicle cross the central dashed line?" (*Perception* component of situation awareness) "Do you have priority over oncoming traffic at the road narrowing?" (*Comprehension*) and "Can you turn after this oncoming truck has passed?" (*Projection*). Participants were required to verbally respond to all prompts. The number and frequency of prompts decreased with progression through the series of videos, such that the fifth and final intervention video contained none. The aim was to promote increasingly independent looking behaviour and situation awareness over the course of the intervention. A series of red arrow cues were also inserted into each intervention video, at onsets occurring 12 s prior to every junction for which the participant was required to initiate relevant behaviours; notably, looking around, signalling and manoeuvring. There were three types of arrow cues, signifying whether a left turn, a right turn, or continuing straight ahead was required. Table 1 shows the numbers of auditory prompts and number of cued junctions for each of the videos.

An instructive video was created in Camtasia Studio 8 (Okemos, MI). It was inserted at the beginning of the intervention to introduce participants to the study and the routes, and to develop their understanding of the relationship between eye movements and attention, including the use of peripheral vision to detect potential hazards whilst maintaining a distal fixation point (see Fig. 2). It also enabled them to practise behaviours relating to turns that they would need to exhibit during the immersive protocol. The instruction video lasted for 14.5 min and played at the start of the training protocol.

Immersive setup. Fig. 3 illustrates the intervention setup, including a pilot participant and the researcher. The edited videos were projected via three short-throw projectors (Optoma GT1080e), onto three rear projection screens mounted on a bespoke tubular aluminium frame. This provided an immersive setup with an approximately 220° field-of-view that required and promoted head movements around junctions. In the centre of the setup was a 13-inch-frame child's bicycle (Hardrock; Specialized Bicycle Components, Inc., CA), mounted on a cycle trainer (UniSky; Jinhua City, China). The front brake lever was connected to a laptop computer which provided a visual indication to the researcher every time the brake lever was depressed.

Mounted to the rear of the frame were two laptop devices. The right-hand one showed alternating graphics of cars in varying colours, against a still image street scene backdrop. The left-hand device displayed the

Table 1
Intervenion Videos – Summary Data.

Video Number	Duration (min:sec)	Number of Auditory Prompts	Number of Cued Junctions
1	6:14	28	7
2	7:41	25	7
3	11:12	22	12
4	11:01	14	10
5	11:44	0	11

Fig. 2. Instructive Video Screenshot.

Fig. 3. Immersive Intervention Setup.

same backdrop, but with alternating presence and absence of a cyclist in the foreground. The participants' task was to identify the car colour and presence/absence of the cyclist, respectively, when approaching a junction; this encouraged rearward looking behaviour that comprised head turns and upper body rotation. If the red arrow cue indicated a right turn or continue straight ahead at the upcoming junction, then the participant was only required to look over their right shoulder and identify the colour of the car. If the red arrow cue indicated a left turn at the approaching junction, the participant had to first look over their right shoulder and identify the colour of the car, then identify whether a cyclist was present or absent. These looking behaviours are in accordance with the National Standard for cycle training (DfT & DVSA, 2019).

Participants wore Tobii Pro 2 eye tracking glasses (Tobii; Stockholm, Sweden) throughout the protocol. These glasses were wirelessly connected to a laptop computer housing Tobii Pro Lab software (Tobii, v. 1.181). Participants' eye and head movements were continuously recorded throughout the intervention, which enabled the researcher to provide instant feedback regarding participants' looking behaviour.

Participants' behaviour, including verbal responses to the auditory prompts, were recorded by the researcher using a bespoke intervention checklist that identified the nature and timing of all auditory prompts and junction-related cues, for each video. The researcher also provided verbal responses to the participant, to denote the correctness of their answer (e.g., "That is correct. Well done") and/or to provide corrective information (e.g., "There was a pedestrian on the left").

Post-test and retention

The post-test and retention test included online and on-road components. The online component utilised the same equipment and materials as the baseline phase and comprised the cycling self-efficacy test and online situation awareness test. The on-road assessment examined the extent to which knowledge and skills acquired during the intervention would transfer to real-world cycling performance.

Situation awareness tests. These were completed as per the baseline phase.

Cycling self-efficacy questionnaire. The exact same questions and scales from baseline were used in the post-test and retention test.

On-road assessment. The on-road assessments took place in a residential area, over a 0.8-mile route which started and finished at the authors' research institution. Participants were required to perform three lefthand turns, five righthand turns, to pass through a pedestrian crossing twice, to navigate a crossroad junction, and to pass a total of seven side roads (3 on their left, 4 on their right). Participants were required to bring their own roadworthy cycle and helmet. They were each provided with a fluorescent tabard to wear during each assessment by the local Bikeability instructor team; the children were encouraged to keep and use these after the study.

Qualified Bikeability cycle instructors, who remained unaware of the participant groupings throughout the study, performed the one-to-one assessments, by following behind the participant on the assigned route and monitoring their on-road cycling performance. Once the route had been completed, the instructor completed a checklist comprising 11 items which collectively summarised the child's on-road cycling performance vis-à-vis the four Core Functions (*Observation*, *Communication*, *Position*, and *Priorities*); for example, "The child looked over their right shoulder" is one of four items used to assess the child's observation-related behaviours. The instructors indicated the frequency with which each child demonstrated the behaviours on a 4-point Likert-type scale by circling one of the following labels (scoring in brackets): *Never* (0), *Occasionally* (1), *Frequently* (2) or *Always* (3). An additional item, *There was no opportunity to demonstrate this*, was also available, with no associated score. We propose that these behaviours, which can be observed to varying extents, are a combination of antecedents, processes, and consequences of situation awareness. For example, when approaching a junction, a cyclist must look around, having positioned themselves appropriately in the lane, adjust their position according to situational requirements, and communicate their intentions to other road users by hand signalling, then act in accordance with multiple road user priorities, including their own – foremost of which is their safety. Hence, we used these assessments as a proxy for participants' demonstration of situation awareness.

Procedure

Institutional research ethics committee approval was obtained prior to commencing data collection. Written informed consent was obtained from all participants and their parents prior to their participation and their right to withdraw at any point, to no personal disadvantage whatsoever, was reiterated verbally. Throughout the study, the UK was in various stages of lockdown due to the Covid-19 pandemic and so many of the tests were conducted online for baseline, post-test and retention phases. However, the immersive intervention was conducted face-to-face in the laboratory and the on-road assessments were in person. All UK government and institutional regulations and requirements at the time were strictly adhered to.

Baseline

Those children and their parents who agreed to take part arranged an initial online meeting with the researcher for the baseline phase. In this phase, the child and parent/carer provided demographic information and the child reported their typical cycling behaviour before completing the cycling self-efficacy questionnaire. Thereafter, the researcher explained the online situation awareness test, which included advising the participant to maximise the video window for each trial, so that they could see all available information. The child then viewed and responded to all 20 video clip scenarios, which concluded the meeting.

Immersive training intervention

Each Intervention group participant and a parent/carer attended the lab on one occasion. Prior to their visit, all parents confirmed that neither they nor their child were symptomatic for Covid-19, and their forehead temperatures were checked prior to entering the building. All parties wore facial masks and observed the current UK social distancing rules; the researcher wore additional personal protective equipment. All surfaces and equipment were sanitised regularly, both within and between participant testing sessions.

Once the protocol had been explained to the child and their parent/carer, the researcher handed the eye tracking glasses to the participant for them to wear. The researcher checked that the glasses and cycle saddle height were comfortable for the participant, then asked them to straddle the crossbar of the bicycle to view the on-screen instruction video. During the instruction video, the participant was required to demonstrate that they were able to perceive various elements of the street scene presented to them, both with and without visual fixation on those elements. They also had three attempts to demonstrate appropriate head turning and signalling behaviour for each of three different junction navigations – straight ahead, left turn and right turn – when on-screen cues indicated that they should do so. Participants were also encouraged to adopt a distal viewing gaze strategy like that used by drivers (Kadar et al., 2011), to promote anticipatory gaze behaviour.

Once the participant had completed the instruction video, and had the opportunity to ask any questions, the researcher explained that the first intervention video was about to commence. The researcher also explained that the participant should pedal the bicycle at a pace they deemed to reflect the pace indicated in the video, which included coming to a stop, and that they should turn the handlebars in a way that is consistent with turns in the video; the researcher explained that the participant could put their foot on the floor at these points. They also reiterated that the participant would hear questions and should respond out loud to those questions.

Using the intervention checklist as a guide, the researcher ensured that the participant responded to all prompts and verbally acknowledged relevant participant behaviours including eye movements, head turning, hand signalling, braking, and hazard identification. The participant completed all five immersive videos sequentially, taking breaks in between as necessary. Participants were required to navigate 47 virtual junctions, 7 of which comprised cycling straight ahead. The remaining 40 junctions comprised 21 right turns and 19 left turns – thereby requiring participants to perform 21 righthanded signals and 19 lefthanded signals, respectively.

Post-test and retention

Online assessments. The participants completed the online post-test phase within 1–45 days ($M = 13.6$, $SD = 11.61$; median = 11 days) of completing the Baseline phase. The participants completed the online retention test within 8–88 days ($M = 35.73$, $SD = 18.78$; median = 29 days) after completing the online post-test. In these phases, participants reported their cycling behaviour since the Baseline phase and rated their cycling self-efficacy, as well as completing the online situation awareness test. This followed the same procedure as in the Baseline phase.

Table 2 shows descriptive statistics to illustrate the durations of the intervening periods between baseline and post-test phases, and between post-test and retention phases, by Group. There was a significant between-group difference for the intervening period between baseline and post-test, $t(30) = 2.94$, $p = 0.006$, 95 % CI = 0.24 – 1.81; this period was longer for the Control group. There was no difference for the intervening period between post-test and retention phases, $p = 0.90$.

On-road assessments. Participants completed their first on-road assessment as part of the Post-test within 1–41 days ($M = 7.15$, $SD = 15.80$; median = 6 days) of completing the online component of the Post-test. Participants completed a second on-road assessment as part of the Retention test, 7–99 days ($M = 35.61$, $SD = 21.14$; median = 33 days)

Table 2
Baseline-to-Post-test and Post-test-to-Retention Intervening Periods, by Group.

Measures	Intervening Period	Group	
		Intervention	Control
Self-Efficacy Judgements and Situation Awareness Tests	Baseline-Post-test	M = 57.71 days SD = 13.62 days Mdn = 14 days Range = 3–45 days	M = 8.00 days SD = 4.82 days Mdn = 7 days Range = 1–19 days
	Post-test-Retention	M = 19.00 days SD = 22.23 days Mdn = 26 days Range = 8–88 days	M = 37.00 days SD = 14.89 days Mdn = 35 days Range = 12–77 days
On-Road Assessments	Post-test-Retention	M = 41.47 days SD = 25.62 days Mdn = 33 days Range = 7–99 days	M = 29.38 days SD = 13.15 days Mdn = 31.5 days Range = 10–56 days

after completing the Post-test on-road assessment. Table 2 shows descriptive data, by Group; there were no significant between-group differences in intervening period, $p = 0.10$.

For each on-road assessment, a Bikeability instructor and a researcher met the participant and their parent/carer during daylight hours at an on-campus location next to the start of the route. The instructor explained the route to the child and parent/carer and answered their questions before checking the roadworthiness of the participant's cycle. Although the on-road assessments were conducted outdoors, social distancing was still observed. The instructors were blinded to participant groupings.

The instructor and participant cycled to the route start along a 30 m stretch of campus road, whereafter the instructor indicated that the participant should pull onto the public road when it was safe to do so. The instructor cycled behind the participant at approximately 5–10 m throughout the duration of the route and spoke only to indicate the direction in which the participant should turn at each junction. They would only intervene when a participant cycled in a way that might endanger themselves or others. Once they had returned to campus, they joined the parent and researcher and dismounted from their cycles. The instructor completed a paper copy of the on-road assessment checklist confidentially, before handing it to the researcher.

Data pre-processing

On-road assessments. The Bikeability instructors' on-road assessment checklist ratings were averaged for each participant, for *Making good and frequent observations* (Items 1, 2, 3, 4), *Communicating intentions clearly to others* (Items 5 & 6), *Choosing and maintaining the most suitable riding positions* (Items 7, 8, 9), and *Understanding priorities on the road* (Items 10 & 11). The response option *There was no opportunity to demonstrate this* was selected for four items in total; these did not contribute to the average scores.

Intervention looking behaviour. Intervention participants'. looking behaviour was characterised via data obtained from the eye tracking glasses and researcher-recorded checklist observations. They are described below.

2.3.4.2.1 Head Turning at Junctions. Head turning behaviour at virtual and real-world junctions is similar (O'Hern et al., 2017). The percentage of junctions at which participants made a head turn was calculated retrospectively using the eye movement recording. A head turn was defined as >45 degrees of head rotation. Head turn behaviour at *T*-junctions, crossroads, roundabouts, and side roads was examined.

2.3.4.2.2 Initial Head Turn Direction at T-Junctions and Crossroads. Rightward initial head turns at many junctions are important for cyclists' safety when considering that the immediate threats typically approach from the right at T junctions and crossroads in the UK, and evidence suggests that cyclists' visual attention is directed more toward threats (Kovácsová et al., 2018); drivers show similar threat-related allocation of attention – sometimes at the expense of the cyclist (Jannat et al., 2020). Therefore, the percentage of rightward initial head turns at *T*-junctions and crossroads, for which the participant was required to cross and/or merge with traffic moving perpendicularly to their line of travel, was determined using data obtained via the eye tracking glasses.

2.3.4.2.3 Rearward Looking Behaviour. Given the prevalence of potential hazard of rearward approaching vehicles (Feng et al., 2018), the frequency with which participants correctly looked behind them when approaching a junction and identified the colour of the vehicle in the right-hand display (required at all cued junctions) and the presence/absence of a cyclist in the left-hand display (cued left-hand turns only) was calculated and converted into a percentage. This was recorded by the researcher throughout the intervention using the intervention checklist. These data were only available for the first four routes.

2.3.4.2.4 Gaze Behaviour. Eye movements are a useful index of cyclists' hazard perception (Kovácsová et al., 2018; Rupi & Krizek, 2019). We analyzed participants' gaze behaviour in relation to the front screen, on straight sections of roads where no turns were required, because preliminary inspection of the gaze data in relation to the lateral screens showed that participants' point-of-gaze was highly dispersed and some distance from relevant objects (e.g., approaching vehicles) when they turned their heads to look at them. This might have reflected their use of peripheral vision, which can expedite decision-making when stimuli are large and salient (Perkovic et al., 2022), but our study design does not allow us to draw such conclusions; hence, these data were likely to be uninformative, or even misleading.

Consequently, we analyzed footage acquired from 17 participants with a total duration of 293.31 min (Route 1 mean per participant [M] = 2.77 mins, SD = 0.69 mins; Route 2 M = 4.67 mins, SD = 1.08 mins; Route 3 M = 4.78 mins, SD = 1.59 mins; Route 4 M = 3.79 mins, SD = 1.04 mins; Route 5 M = 4.49 mins, SD = 1.55 mins). Fig. 4 illustrates four Areas of Interest (AOIs) which were created to represent distal looking (A), proximal looking (B), leftward looking (C) and rightward looking (D); these zones were chosen because they collectively represent anticipatory gaze behaviour (A and B) and visual attention to peripheral stimuli (C & D; cf. Vanstenkeeste et al., 2017). We calculated percentage dwell times for each of these interest areas.

Note: A = Distal, B = Proximal, C = Leftward, D = Rightward.

Data analysis

All data were screened for outliers and non-normality prior to analysis. Where appropriate, Mauchly's Test of Sphericity was used to determine whether the assumption of sphericity had been violated and if so Greenhouse-Geisser adjustment was applied. Partial eta squared (η_p^2) is reported as the effect size measure. The alpha level for significance was set at $p < 0.05$.

Participants' cycling behaviour. Independent samples t-tests were used to compare the cycling that the two groups performed outside of the study, both at baseline and during the study; and to compare their cycling self-efficacy and situation awareness at baseline.

Immersive training intervention. The above measures were analysed to

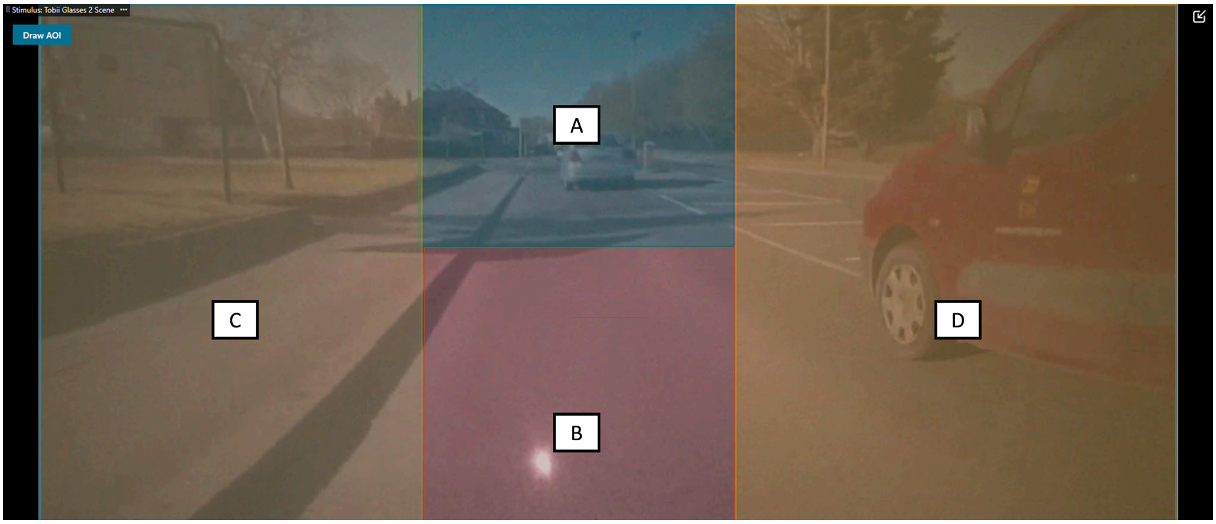


Fig. 4. Screenshot from Tobii Pro Lab Software: Gaze Data Analysis AOIs (labels overlaid).

observe changes across the routes. A 5 (Route) × 5 (Junction Type) repeated measures ANOVA was used to analyse head turn behaviour. A one-way repeated measures ANOVA was used to compare the percentage of rightward initial head turns at *T*-junctions and crossroads across the five routes. To analyse Rearward Looking behaviour across the four routes, a one-way repeated measures MANOVA was used to analyse the combined dependent measures. Dwell times were analysed using a 4 (AOI) × 5 (Route) repeated measures ANOVA. Follow-up polynomial contrasts and/or and Bonferroni-corrected pairwise comparisons were conducted on all significant main effects where appropriate.

Post-test and retention. The two groups' scores were compared at post-test and retention phases, for cycling self-efficacy, situation awareness, and on-road assessments. For cycling self-efficacy scores, a 2 (Group) × 2 (Phase) mixed MANOVA was conducted on the combined dependent measures of *Navigating junctions*, *Making good and frequent observations*, *Choosing and maintaining the most suitable riding positions*, *Communicating intentions clearly to others*, *Understanding priorities on the road,* and *Responding to hazards*. A 2 (Group) × 2 (Phase) mixed ANOVA was used to analyse situation awareness test scores. For on-road assessments, a 2 (Group) × 2 (Phase) mixed design MANOVA was applied to the combined dependent variables *Making good and frequent observations, Communicating intentions clearly to others*, *Choosing and maintaining the most suitable riding positions*, and *Understanding priorities on the road.* Significant main effects were followed up with univariate tests.

Results

Baseline

Cycling behaviour

Table 3 summarises the two groups' self-reported cycling behaviour and experience. Data screening revealed no outliers, but *days elapsed since Bikeability Level 2 training* data were non-normal, with skewness of 2.20 ($SE = 0.43$) and kurtosis of 3.11 ($SE = 0.85$); hence, nonparametric analyses were applied to these data. There were no significant differences in number of years cycling unaided, $t(31) = 0.80$, $p = 0.43$, 95 % CI: −0.59 – 1.36; average number of cycle rides per week, $t(31) = 1.24$, $p = 0.90$, 95 % CI: 0.06 – 0.50; or days elapsed since Bikeability Level 2 training, $U = 93.00$, $p = 0.63$, $r = 0.02$, 95 % CI: −74.34 – 276.20.

Cycling self-efficacy

Baseline cycling self-efficacy scores for the two groups are presented in Table 4. Independent samples t-tests revealed no significant

Table 3
Self-Reported Cycling Behaviour and Experience, by Group.

		Intervention Group (n = 17*)	Control Group (n = 16*)
Number of years of cycling unaided	Mean (SD)	4.59 (1.66)	4.97 (1.01)
	Median	6	4
	Range	1–6	3–6
Cycle rides per week	Mean (SD)	2.00 (1.12)	2.06 (1.73)
	Median	2	1
	Range	1–5	1–7
Days elapsed since Bikeability Level 2 training	Mean (SD)	61.38 (140.59)	162.31 (271.61)
	Median	20.5	26
	Range	5–583	6–647

* Intervention Group n = 16, Control Group n = 13, for *Days elapsed since Bikeability Level 2 training*, due to missing data.

Table 4
Cycling Self-Efficacy Scores, by Group and Phase.

Mean (SD)	Group*	Baseline	Post-Test	Retention
Navigating Junctions	Intervention	87.80 (10.43)	92.76 (11.48)	91.27 (15.32)
	Control	82.59 (17.25)	85.31 (15.29)	86.62 (18.51)
Observation	Intervention	80.90 (21.49)	85.82 (16.18)	86.28 (18.032
	Control	85.38 (10.43)	84.83 (14.38)	87.38 (11.73)
Communication	Intervention	82.00 (24.43)	83.32 (23.23)	87.21 (21.52)
	Control	81.27 (14.55)	82.23 (19.04)	86.54 (12.41)
Position	Intervention	84.68 (22.85)	83.09 (27.03)	85.32 (24.98)
	Control	90.50 (16.09)	91.96 (14.07)	93.31 (11.00)
Priorities	Intervention	81.66 (24.05)	86.28 (19.29)	87.51 (19.12)
	Control	80.06 (17.79)	79.08 (20.03)	83.23 (20.07)
Responding to Hazards	Intervention	86.06 (11.93)	91.47 (11.70)	87.12 (18.74)
	Control	85.46 (14.81)	83.46 (19.38)	85.46 (14.72)

* Intervention group n = 17; Control group n = 13 due to missing data.

differences between the two groups at baseline for cycling self-efficacy scores regarding *Navigating junctions* ($p = 0.64$), *Making good and frequent observations* ($p = 0.33$), *Communicating intentions clearly to others* ($p = 0.79$), *Choosing and maintaining the most suitable riding positions* ($p = 0.54$), *Understanding priorities on the road* ($p = 0.93$), and *Responding to hazards* ($p = 0.78$).

Online situation awareness test

An independent samples t-test showed no significant difference in the two groups' situation awareness scores at baseline for the Control group ($M = 53.13$ %; $SD = 11.96$) and Intervention group ($M = 46.47$ %; $SD = 12.72$), $t(31) = 1.55$, $p = 0.13$.

Post-Test and retention

Cycling behaviour during the study

There was no significant difference in self-reported minutes of cycling between the baseline and retention phases for the Control group ($M = 100.00$; $SD = 125.01$) and Intervention group ($M = 105.00$; $SD = 147.81$), $t(31) = -0.11$, $p = 0.92$.

Cycling self-efficacy

Table 2 summarises the two groups' cycling self-efficacy scores by Group and Phase. The data for all variables were normally distributed and contained no outliers. A two-way mixed MANOVA revealed no significant Group × Phase interaction, $F(6,23) = 0.32$, $p = 0.92$, $\eta_p^2 = 0.08$, and no significant main effect for Group, $F(6,23) = 1.89$, $p = 0.13$, $\eta_p^2 = 0.33$, or Phase, $F(6,23) = 0.94$, $p = 0.48$, $\eta_p^2 = 0.20$.

Online situation awareness tests

The boxplots in Fig. 5 depicts the median situation awareness test scores for the Control group and Intervention group, their interquartile ranges and associated 95 % Confidence Intervals, at baseline and in the post-test and retention test. Values were normally distributed and contained no outliers. A two-way mixed ANOVA yielded no significant Group × Phase interaction, $F(1,31) = 0.06$, $p = 0.82$, $\eta_p^2 = 0.002$, and no main effect for Group, $F(1,31) = 1.95$, $p = 0.17$, $\eta_p^2 = 0.06$, or Phase, $F(1,31) = 0.57$, $p = 0.46$, $\eta_p^2 = 0.02$.

On-road assessment performance

The boxplots in Fig. 6 depict the median on-road assessment scores for each of the four Core Functions, their interquartile ranges and associated 95 % Confidence Intervals, organised by Group and Phase. The data for all variables were normally distributed and contained no outliers. A two-way mixed MANOVA showed no significant Group × Phase interaction, $F(4,28) = 2.08$, Hotelling's Trace $= 0.19$, $\eta_p^2 = 0.23$, $p = 0.11$; and no main effect of Phase, $F(4,28) = 1.32$, Hotelling's Trace $= 0.19$, $\eta_p^2 = 0.61$, $p = 0.29$.

However, there was a significant main effect of Group, $F(4,28) = 5.02$, Hotelling's T $= 0.72$, $\eta_p^2 = 0.42$, $p = 0.004$. Follow-up univariate tests revealed significant differences between the groups' scores for all four Core Functions: compared to the Control Group, the Intervention Group were better at *Making good and frequent observations* (Observation; $F[1,31]) = 16.53$, $\eta_p^2 = 0.35$, $p = 0.0003$,); *Communicating intentions clearly to others* (Communication; $F[1,31]) = 13.70$, $\eta_p^2 = 0.31$, $p = 0.001$); *Choosing and maintaining the most suitable riding positions* (Position; $F[1,31]) = 7.41$, $\eta_p^2 = 0.19$, $p = 0.01$); and *Understanding priorities on the road, particularly at junctions* (Priorities; $F[1,31]) = 6.88$, $\eta_p^2 = 0.18$, $p = 0.01$). This suggests the immersive intervention positively impacted on-road cycling behaviour.

Immersive training intervention

Head turn behaviour at junctions

Fig. 7 shows the percentage of junctions at which participants turned their heads beyond 45°, grouped by junction type and route. A two-way repeated measures ANOVA revealed no main effect of *Route,* but there was a main effect of *Junction Type*. Mauchly's Test of Sphericity

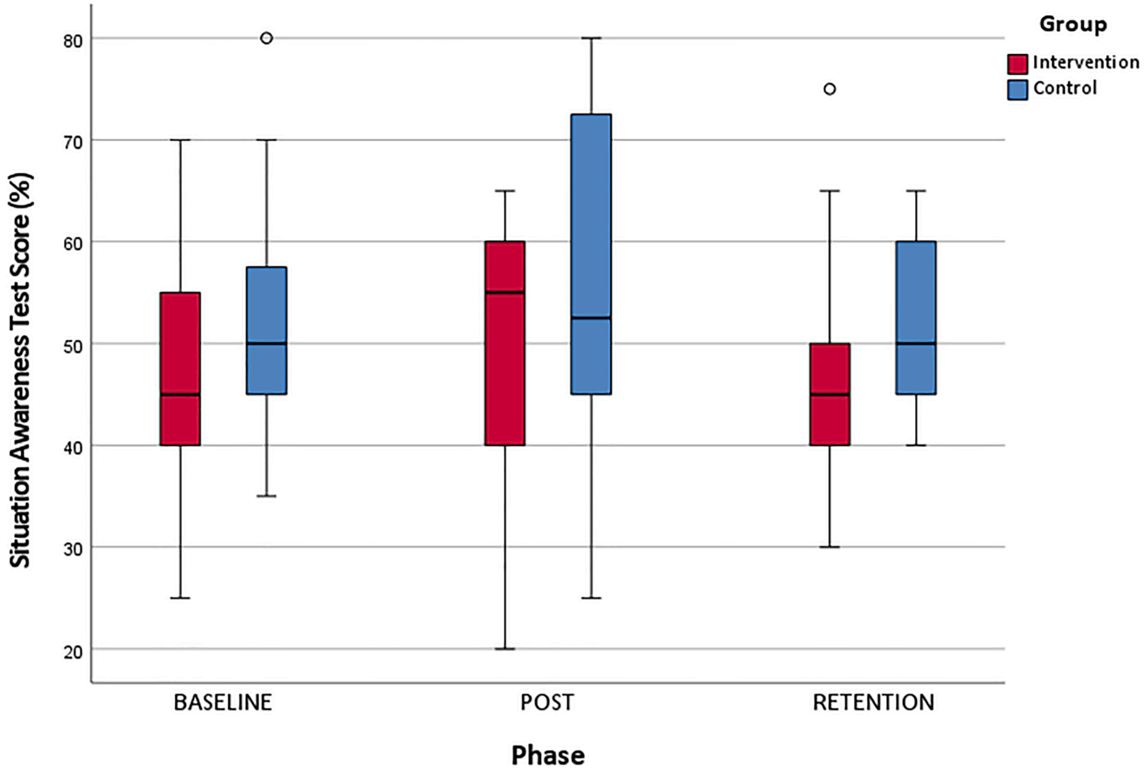


Fig. 5. Situation Awareness Test Scores, by Group and Phase.

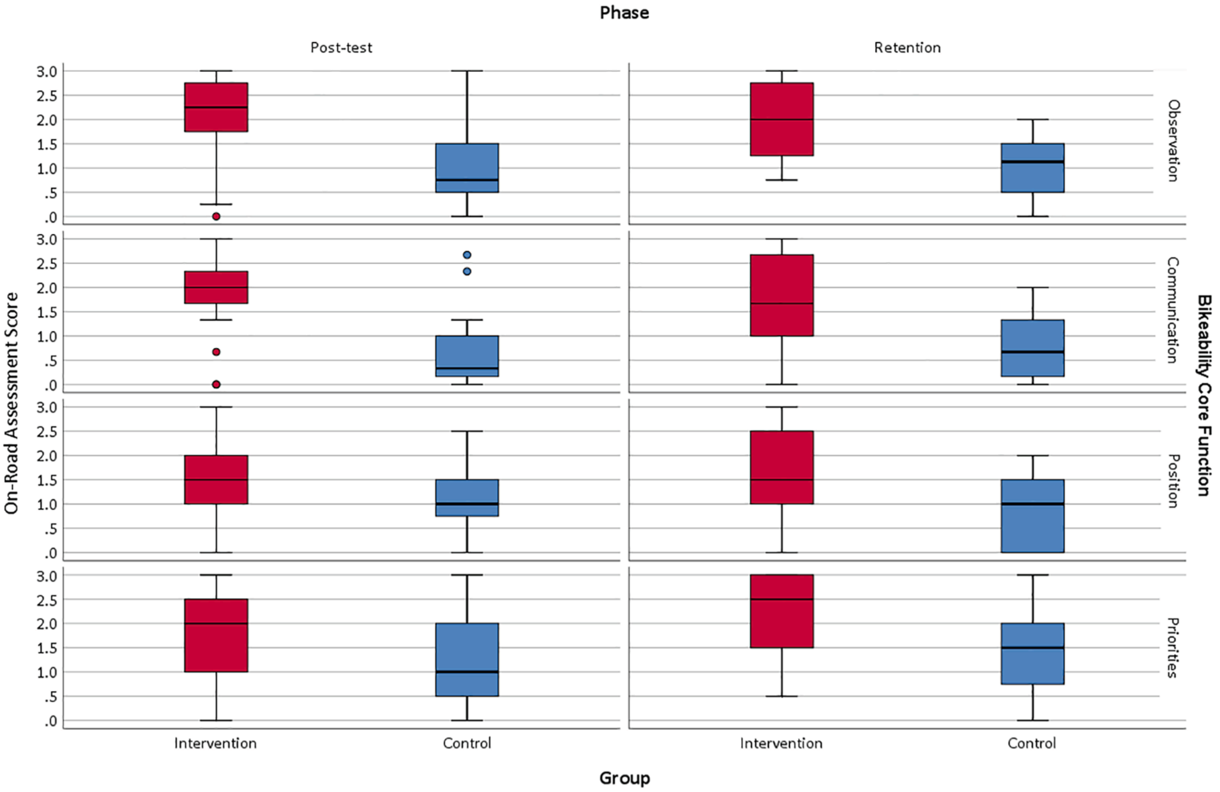


Fig. 6. On-Road Assessment Scores, by Group and Phase.

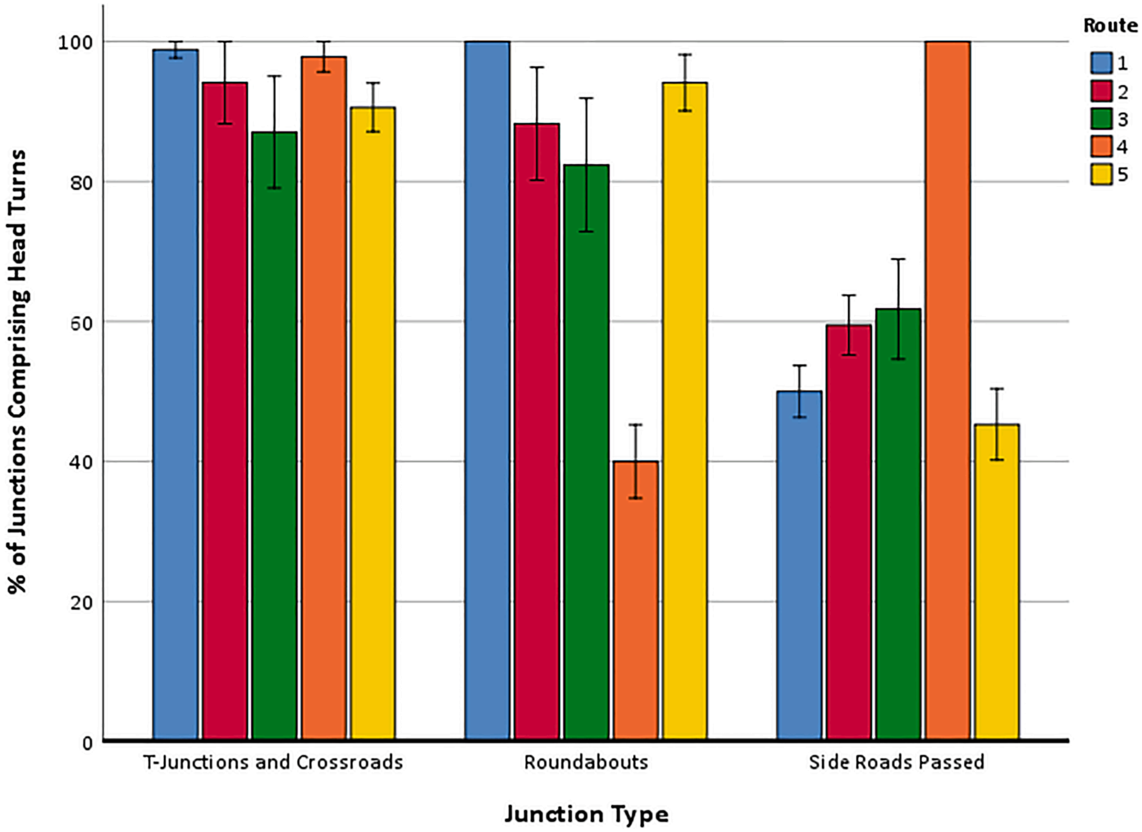


Fig. 7. Percentage of Head Turns, by Junction Type and Route.

indicated that the assumption of sphericity had been violated for *Junction Type*, $\chi^2(2) = 7.60$, p = 0.02, so Greenhouse-Geisser adjustment was applied: $F(1.43,22.90) = 74.56$, $\eta_p^2 = 0.82$, $p = 9.02\times10^{-13}$. A follow-up polynomial contrast revealed a linear trend across the three junction types, $F(1,16) = 271.84$, $\eta_p^2 = 0.94$, $p < 0.001$. Follow-up Bonferroni-corrected pairwise comparisons showed that head turns were more prevalent at *T*-junctions and crossroads ($M = 93.68$ %; $SD = 11.92$ %) than at roundabouts ($M = 80.94$ %; $SD = 11.92$ %), for which head turns were more prevalent than when passing side roads ($M = 63.3$ %; $SD = 10.84$ %).

Note: Error bars represent ± 1 standard error.

Initial head turn direction at T-junctions and crossroads

Fig. 8 shows the percentages of rightward initial head turns at *T*-junctions and crossroads – i.e., those toward the immediate oncoming traffic, by Route. A one-way repeated measures ANOVA was applied to the data. There was no main effect of *Route*, $p > 0.05$.

Note: Error bars represent ± 1 standard error.

Rearward looking behaviour

Table 5 shows a summary of how frequently Intervention group participants correctly identified the colour of the vehicle to the rear (required at all cued junctions) and the presence/absence of a cyclist (cued left-hand turns only).

A one-way repeated measures MANOVA was applied to the data to examine overall rearward looking behaviour. There was a significant main effect of *Route*, $F(6,90) = 3.55$, Pillai's Trace = 0.38, $\eta_p^2 = 0.19$, $p = 0.003$. A follow-up polynomial contrast revealed a linear trend across the four routes for vehicle identification, $F(1,15) = 14.36$, $\eta_p^2 = 0.49$, $p = 0.002$: rearward looking behaviour over the right shoulder improved throughout the immersive training protocol.

Table 5
Correct Identifications of Rearward Vehicle Colour and Cyclist Presence/Absence.

Route	Vehicle Colour (%)		Cyclist Presence/Absence (%)	
	Mean	SD	Mean	SD
1	75.89	21.33	93.75	25.00
2	89.92	14.95	91.18	19.65
3	93.58	11.02	92.65	11.74
4	98.69	3.69	94.12	13.10

Table 6
Average Percentage Dwell Times, by Interest Area and Route.

Route	Distal	Proximal	Leftward	Rightward
1	59.70	8.17	8.15	7.64
2	58.21	14.73	8.41	6.11
3	53.03	17.89	6.68	7.80
4	58.34	13.09	5.74	5.70
5	50.57	14.91	6.40	9.26

Gaze behaviour

Table 6 shows gaze dwell times, by interest area and route. A two-way ANOVA revealed a significant interaction of AOI and Route, $F(12,132) = 2.68$, $\eta_p^2 = 0.20$, $p = 0.003$; significant follow-up tests were multitudinous and are consequently provided in the Supplemental Materials, but while visual inspection showed that this interaction was somewhat driven by more distal looking in all routes relative to proximal, leftward and rightward gaze when considering all comparisons with other routes (e.g., distal looking in Route 1 relative to leftward looking in Route 3), follow-up simple effects analyses showed that, for proximal looking, there were differences across the five routes, $F(4,44) = 5.24$, $\eta_p^2 = 0.32$, $p = 0.002$; all other analyses were nonsignificant, $p > 0.05$. Bonferroni-corrected pairwise comparisons showed that this was driven by significant differences between proximal dwell times for Route 1 relative to each of Route 2 ($p = 0.002$) and Route 3 ($p = 0.001$).

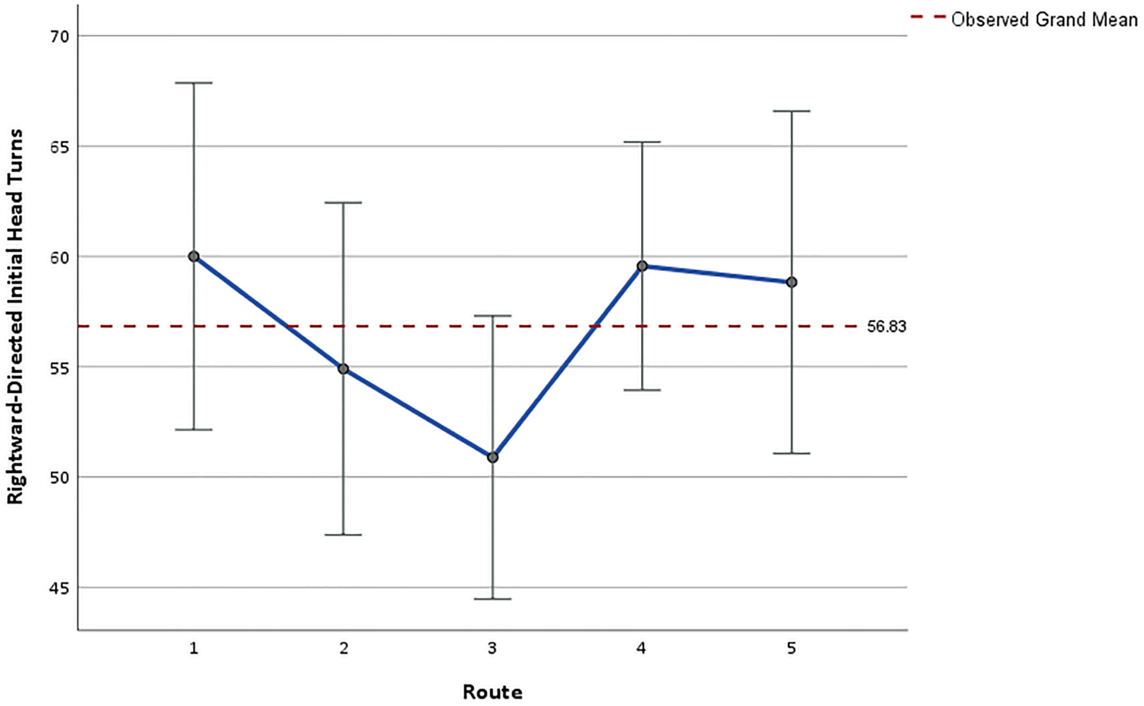


Fig. 8. Percentage of Rightward Initial Head Turns at *T*-Junctions and Crossroads.

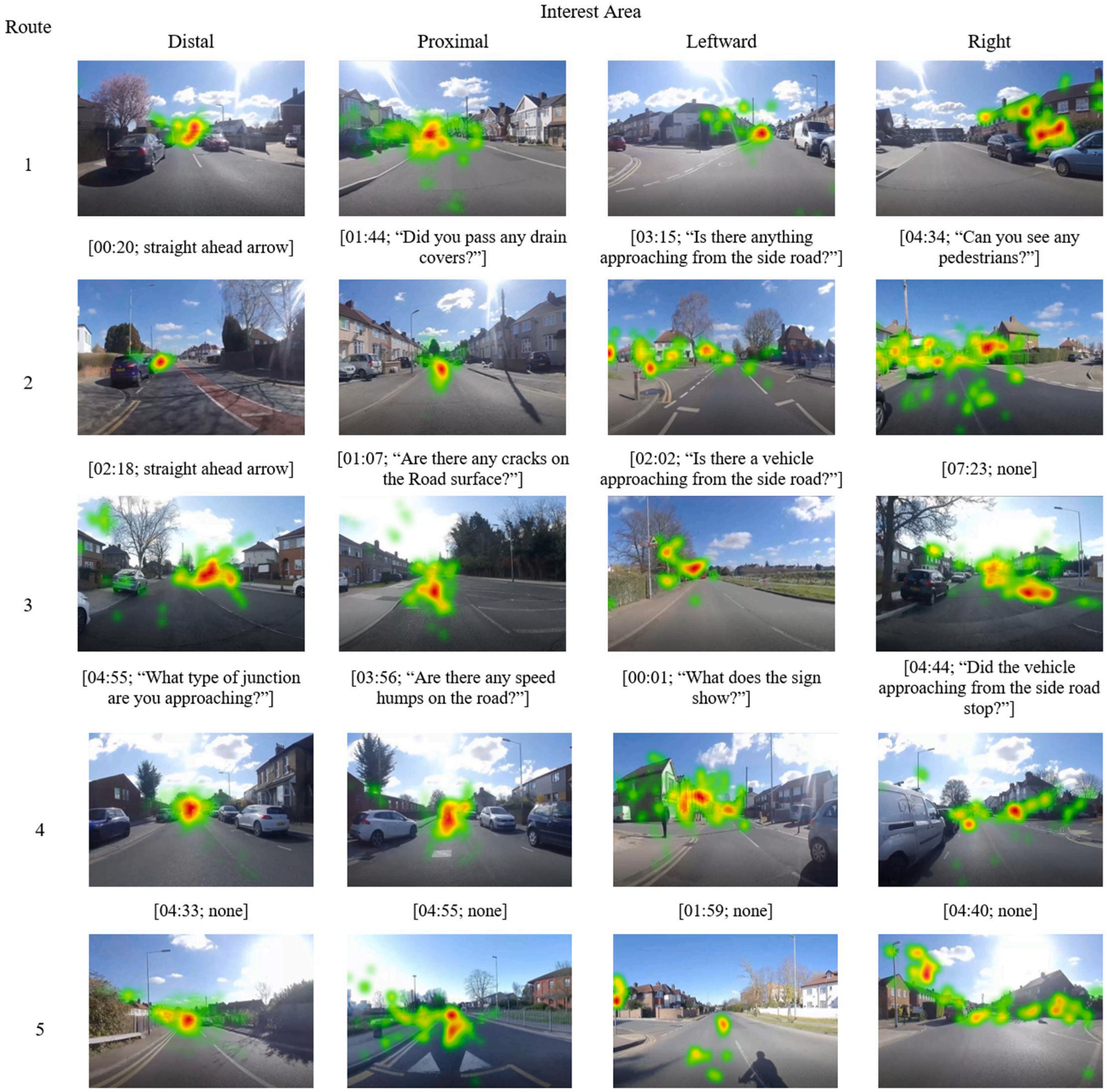
There was also a significant main effect of AOI, $F(3,33) = 181.01$, $\eta_p^2 = 0.94$, $p = 1.4\times10^{-20}$. Follow-up Bonferroni-corrected pairwise comparisons showed that participants adopted a distal gaze strategy ($M =$ 55.88 %; $SD =$ 8.16 %) more frequently than proximal ($M =$ 14.47 %; $SD =$ 7.55 %), leftward-looking ($M =$ 7.19 %; $SD =$ 4.29 %) and rightward-looking ($M =$ 7.97 %; $SD =$ 4.49 %) strategies; and more frequently proximal than both leftward- and rightward-looking, all p's < 0.05. There was no main effect of Route, $p > 0.05$.

Fig. 9 contains heat maps to illustrate participants' gaze behaviour in relation to various auditory prompts and on-screen cues, and their gaze behaviour when no prompts or cues were provided. Each heat map represents the aggregate of all participants' eye movements, for a 2-second epoch beginning in the frame immediately following the cessation of a prompt or cue, when one was available; those without prompts or cues were selected at random. Heat maps are provided to illustrate participants' gaze behaviour in relation to each of the four interest areas (*Distal*, *Proximal*, *Leftward*, *Rightward*) for each of the five routes, whether prompted/cued or otherwise (e.g., when passing a side road with no associated prompt or turn [e.g., Rightward heat maps for Routes 4 & 5]).

Note. The timestamp and associated prompt or on-screen cue immediately prior to the 2-second epoch are detailed in square brackets beneath each screenshot; 'none' means there was neither a prompt nor a cue.

Discussion

We conducted a pilot study to determine whether a video-based immersive cycle training intervention comprising real-world POV footage could improve young children's situation awareness and observational skills when cycling on roads. There was a marked effect of



Route 1: [00:20; straight ahead arrow] [01:44; "Did you pass any drain covers?"] [03:15; "Is there anything approaching from the side road?"] [04:34; "Can you see any pedestrians?"]

Route 2: [02:18; straight ahead arrow] [01:07; "Are there any cracks on the Road surface?"] [02:02; "Is there a vehicle approaching from the side road?"] [07:23; none]

Route 3: [04:55; "What type of junction are you approaching?"] [03:56; "Are there any speed humps on the road?"] [00:01; "What does the sign show?"] [04:44; "Did the vehicle approaching from the side road stop?"]

Route 4: [04:33; none] [04:55; none] [01:59; none] [04:40; none]

Route 5: [07:42; none] [00:04; none] [01:35; none] [05:55; none]

Fig. 9. Gaze Heat Maps, by Route and Interest Area.

our intervention: trained participants significantly outperformed a control group in on-road cycling, when assessed in relation to the four Core Functions outlined in the UK National Standard for cycling (DfT & DVSA, 2019). These improvements were manifested in observable behaviours on the road, including head turns, hand signalling, positioning within their lane, and awareness of road user priorities – both theirs and others'. The current findings suggest that one or more behaviours required of participants in our immersive video-based intervention positively transferred from the lab to the real-world and may therefore complement current training practices to enhance young cyclists' safety.

However, contrary to our hypotheses, there were no significant changes in intervention group participants' situation awareness, as measured using a series of online video-based tests; this is despite employing an intervention protocol designed to promote their situation awareness. So, on this basis, we cannot conclude that the intervention improved participants' situation awareness. This said, we should acknowledge that video-based assessments may not be the best way to assess road users' situation awareness because the task design does not suitably mimic the demands of the real world (Dicks et al., 2009). Moreover, it may also have been prudent to adapt existing protocols designed to assess drivers and/or cyclists' situation awareness (e.g., Crundall, 2016; Sirkin et al., 2017). However, it is important to note that the UK was in various stages of lockdown in the Covid pandemic during the data collection period, which meant that those data were collected in the participants' homes, under highly variable conditions; for example, on devices with varying screen sizes, and in environments comprising varying degrees of distraction. Hence, it is likely that these assessments were not as sensitive as they might be if conducted under controlled conditions. Accordingly, an appropriate direction for future research would be to determine whether these bespoke tests are sensitive enough to detect changes in children's situation awareness after undertaking immersive cycle training.

No between-group differences in self-reported cycling self-efficacy were apparent in the post-test or retention. Whilst it may be viewed as a positive finding that the intervention group's self-efficacy estimates were not inflated relative to those of the control group, we might have expected a difference to emerge; self-efficacy increases are consistently associated with skill learning improvements (Pascua et al., 2015). However, 13 of the 17 intervention participants reported higher cycling self-efficacy at post-test than at baseline, and 14 reported higher values at retention relative to post-test. Only half of the control group reported increases, at both stages. This said, self-efficacy scores for both groups across all test phases were consistently high despite variable situation awareness scores, which may reflect potential overconfidence in both groups (Bishop et al., 2022). Indeed, there is evidence that children may overestimate their cycling experience – with potential implications for their situation awareness: Twisk and colleagues (2018) assessed the higher-order cycling skills of 11–13-year-old cyclists, using a battery of computerised tests that mimicked real-world traffic conditions and comprised a hazard perception component. One-third of participants missed at least half of all hazards, made poor crossing judgements, and performed worse when in complex scenarios – even though most of them agreed with the statement "I'm an experienced cyclist". Clearly, further research is needed to assess the impact of children's cycling self-efficacy on their cycling behaviour, not least because some evidence suggests that higher self-efficacy is associated with more fluent decision making (Hepler & Feltz, 2012); this should benefit on-road cycling performance. A cycling-specific measure of self-efficacy may be warranted, given the context-specific nature of the self-efficacy construct. Ideally, such a measure would have high predictive validity so that self-efficacy judgements could be used as a proxy for improvements in on-road cycling performance resulting from immersive training – at a fraction of the costs associated with on-road assessments.

The superior on-road performance of the intervention group vis-à-vis observation may be underpinned by improved looking behaviour. Notably, intervention participants' rearward looking behaviour improved over the course of the immersive protocol: they made more correct identifications of vehicle colours over their right shoulders as they approached T junctions, crossroads, roundabouts, and side roads for which manoeuvres were required. During the intervention, participants' head turning behaviour at junctions was most prevalent when the participant was about to cross or merge with traffic at *T*-junctions and crossroads. Roundabouts did not elicit such extensive head turning, which may reflect the greater visibility of vehicles both on and approaching the roundabouts within a comparatively narrow field of view. Despite frequent prompting to check side roads passed, there was little evidence of improvement in this looking behaviour – although the data suggest this was also maintained, even when participants were no longer being prompted by the researcher, in the fifth and final route. Head turning is an underused process measure of attention allocation in cycling studies (Bogacz et al., 2020), one that provides an observable index of visual attention. A worthwhile future research endeavour would be to record the frequency and excursion of cyclists' head movements when cycling on roads, to better understand the utility of head turning behaviour – which was arguably the instructors' primary indicator of participants' observation-related behaviours when performing on-road assessments, because they observed from a rearward position relative to the participant. A useful complement to this would be to assess both intervention and control groups' head movements in novel immersive scenarios, to determine whether the intervention group's superior on-road observational behaviour is truly a direct consequence of the training.

The gaze data analyses showed that participants predominantly adopted a distal gaze strategy, consistent with the detailed instructions we provided at the beginning of the intervention (e.g., see Fig. 2); such gaze is reflective of anticipatory looking behaviour that is known to be adaptive in dynamic naturalistic environments, such as soccer (Gredin et al., 2018) and driving (Land & Lee, 1994). It is also contrary to previous research, which has shown that children of a similar age exhibit more dispersed and lateralized point-of-gaze than adults and tend to look at task-irrelevant elements (Vanstenkeeste et al., 2017). During the instructions, participants were sensitised to how they could detect information in their peripheral vision, particularly movement, whilst maintaining a fixated point-of-gaze; such strategies can reduce saccadic masking and therefore increase information pickup (D'Innocenzo et al., 2017). Importantly, they also maintained this gaze strategy across all five routes despite decreasing auditory prompts in this regard throughout the protocol (see Table 1), which suggests that this behaviour became more autonomous. This said, we note that we cannot infer causality regarding the effects of our initial instructions on their gaze behaviour, but it would also be prudent to explicitly examine these effects in future.

Participants' gaze behaviour also comprised fixations directed towards relevant elements such as road signs (see Fig. 9), which provide information about environmental conditions – information that can sometimes be disregarded or overlooked by experienced road users (Bongiorno et al., 2016). Evidence suggests that improvements in child cyclists' attentiveness may help to reduce collisions in which they are involved (Salmon et al., 2022). Given the importance of gaze behaviour (e.g., Vansteenkiste et al., 2017) and head turn behaviour (e.g., Bogacz et al., 2020) for hazard perception when cycling, the seemingly adaptive behaviours we observed in participants' gaze behaviour across the intervention highlight the potential benefits of immersive video-based interventions to improve cycling behaviour in children. However, we did not assess the children's gaze behaviour during the on-road assessments, which researchers should look to do – although changes in hazard detection are not always accompanied by changes in eye movements (Zeuwts et al., 2017a).

It is noteworthy that there were two drivers of the significant interaction in the eye movement data. The first of these was the preponderance of a distal gaze strategy, which became influential in the interaction because every comparison of distal looking during any one route with proximal, leftward, or rightward looking in each of the other four routes yielded significant differences. However, simple effects analysis revealed that dwell times in the proximal interest area during Route 1 were significantly lower than in Routes 2 and 3; moreover, proximal dwell times in Route 1 relative to those in Routes 4 and 5 were significant prior to stringent Bonferroni correction for ten multiple comparisons. Closer scrutiny of the auditory prompts given to participants revealed that Routes 1, 2 and 3 included questions which engendered attention to the road surface, including "Did you pass any drain covers?" and "Are there cracks on the road surface?". It is possible that the increases in proximally directed gaze evolved because of these prompts – a notion that also warrants further investigation.

Rightward initial head turns at junctions remained constant across the five routes, which suggests that participants maintained their looking behaviour as their independence increased – i.e., as researcher prompts decreased and then disappeared entirely (i.e., in Route 5). However, participants only looked rightward initially at 56.83 % of all T junctions, crossroads, and roundabouts; more than two-fifths of initial head turns were in a leftward direction, somewhat contrary to previous findings regarding cyclists' visual attention to immediate threats (Kovácsová et al., 2018). Future research should look to examine whether similar looking behaviour is shown in experienced versus inexperienced adult cyclists, and whether training this behaviour transfer positively to on-road cycling performance.

As per the cycle training instructors' use of head turning as an index of participants' observation-related behaviour while cycling, it is likely that, when considering their rearward position during assessments, the instructors construed participants' hand signals as an index of their communication with other road users. When we consider the high proportion of correct vehicle colour identification over the right shoulder, and identification of the presence/absence of a cyclist over the left shoulder (see Table 3) during the intervention, it is likely that the associated hand signals were also performed – although we did not collect data in this regard. This aside, it is possible that there was *positive transfer* of this behaviour to on-road performance too, given the instructors' probable reliance on this behaviour to make their assessments regarding participants' observation-related behaviour.

An unexpected and noteworthy finding was the intervention group participants' superior demonstration of their positioning on the road and awareness of road user priorities during the on-road assessments, relative to the control group. The intervention was not intentionally designed to explicitly improve performance on these Core Functions, although similar positive transfer of untrained behaviours has recently been demonstrated in driving too (Horswill et al., 2022). One tentative explanation for these improvements is that intervention participants' observation and communication had become more automated because of repeated practice throughout the immersive training protocol, freeing up cognitive resources to consciously attend to their position and road user priorities (cf. Magallón et al., 2016). Additionally, the POV perspective aligned with the road positioning guidance laid out in the UK National Standard for cycle training (DfT & DVSA, 2019); hence, it is possible that participants implicitly adopted the same position when cycling during their on-road assessments. If this notion should stand up to closer empirical scrutiny, then this would further strengthen the case for using immersive protocols as a complement to on-road training.

One strength of the present study is that we did not solely rely on looking behaviour during the intervention as a marker of effective perception; to do so would be inherently flawed (Simons & Chabris, 1999). The researcher frequently asked questions of the participants throughout the intervention to ascertain not only the *perception* component of their situation awareness (e.g., "What is that van up ahead doing?"), but also questions to determine their *comprehension* of situations (e.g., "Do you think the driver has seen you?") and ability to anticipate what might happen next (e.g., "Did you expect it to pull out?"; *projection*); these three questions all relate to the same vehicle. Moreover, we incorporated questions to ascertain the projection component of participants' situation awareness, such as "is there a vehicle emerging from the side road?" when no vehicle was visible at the time. This approach may have contributed to the intervention participants' superior performance in the on-road assessments – another assertion that requires further investigation.

Study limitations and future research directions

It is important to note a few limitations of the present study. The first of these is the setup we used in the present study: its size, complexity, and lack of portability may hinder rollout of immersive cycle training to some communities and populations who may benefit most from it, such as those living in remote areas, those who do not own a bicycle, and those with disabilities that make on-road cycling a challenge. A potential alternative may be to use VR headsets to deliver such training, which would reduce financial costs, setup time and the space required (Bogacz et al., 2020; van Paridon et al., 2021). It would also be worthwhile to explore the use of virtual world, as opposed to real-world, footage so that movements of the handlebars, for example, could be coupled with events in that footage; such action-perception coupling is a key determinant of motor learning (van Andel et al., 2017) – one that we did not include in the present study.

Although this study was a pilot test, funded by a scheme intended to support pilot tests that assess the viability of interventions designed to improve road safety in the UK, we wish to acknowledge the potential limitation of the sample size, which was small when we consider the negligible effects that emerged in the online situation awareness tests and cycling self-efficacy judgements; the study was consequently underpowered in respect to these measures; this may have been compounded by the dearth of suitably validated tests for cyclists. However, we should also acknowledge that the effect sizes in the on-road assessments were large, for both the main effect ($\eta_p^2 = 0.42$) and for all univariate analyses (*Observation*, $\eta_p^2 = 0.35$; *Communication*, $\eta_p^2 = 0.31$; *Position*, $\eta_p^2 = 0.19$; *Priorities*, $\eta_p^2 = 0.18$). Nonetheless, there are many possible sources of unobserved heterogeneity in this sample. For example, we did not account for the *quality* of the children's cycling opportunities, which may have exacerbated the size of the effects we observed in the on-road assessment data. Although we collected data regarding their cycling frequency, we did not collect data regarding the types of cycling they undertook during the study – opportunities which could have included on-road cycling practice with their parents; this may be a privilege chiefly afforded to children whose parents form the minority of UK adults aged 30 years and over who have access to a cycle (DfT, 2021). It would be prudent to explore the effects of such social inequalities on cycling behaviour in children and their parents/carers, using large scale survey and/or interview data to do so.

Third, although there were no between-group differences in the time elapsed since participants undertook Bikeability Level 2 training, there was high variability in these timespans, which ranged from a few days to almost two years. Although we originally aimed to recruit participants who had completed this training in the weeks prior to the study, national lockdowns, and a cautious return to face-to-face activities during the Covid-19 pandemic meant that many children in this age group did not have the opportunity to complete this training, unlike their predecessors. This constrained the population of potential participants. Relatedly, there was similarly high variability across participants in the time elapsed between their baseline, post-test, and retention phases – albeit that this only manifested in a significant between-group difference in the baseline-to-pre-test intervening period. Whilst this variability is not ideal, we had to relinquish some experimental control – not least control over the timing of participants' attendance – because of financial, human resource and pandemic-related constraints that we could not circumvent.

Fourth, one aspect of looking behaviour that we did not deliberately promote, is rightward head turning. To our knowledge, there are no data regarding the importance of this behaviour, but for UK cyclists to be suitably aware of road user priorities at junctions, we believe they should prioritise immediate visual attention to vehicles approaching from their right where appropriate; the absence of rightward approaching traffic (*perception*) may be interpreted by the cyclist as providing sufficient time (*comprehension*) for them to advance into the junction safely thereafter (*projection*). A logical future development of immersive training interventions would be to explicitly promote this potentially adaptive looking behaviour and subsequently assess the effects on young children's situation awareness and cycling behaviour.

Finally, although we sought to improve Intervention group participants' situation awareness, we must be clear that we do not have direct evidence that participants' on-road situation awareness improved; we can only make inferences in this regard. For example, we may infer that the superior observation scores of the Intervention group in the on-road assessments were a function of more extensive head turning, both in response to external events and in anticipation of them, which arguably facilitate perception, if not comprehension or projection. Similarly, hand signalling demonstrates the cyclist's awareness not only of an impending junction at which a turn must be made, but also awareness of the required turning direction. Nevertheless, future research in this area should explore alternative methods for performing on-road assessments that directly assess cyclists' situation awareness.

Conclusion

Our pilot test showed that young children who undertook an immersive video-based training intervention designed to improve their looking behaviour and situation awareness outperformed a control group that did not complete the training, in terms of on-road cycling performance – albeit there were no between-group differences in video-based situation awareness test performance. Specifically, intervention group participants' ability to make good and frequent observations, communicate their intentions clearly to others, to choose and maintain the most suitable riding positions, and to understand priorities on the road, particularly at junctions, was demonstrably superior to that of the control group. However, further research is required to determine the extent to which young children's on-road situation awareness can be developed via such interventions.

There are practical implications of the present findings for national policy and practices vis-à-vis cycle training provision in the UK. If the effects we observed in the present study are genuine ones, then immersive training could become a viable adjunct to on-road training; for example, learners' observation and communication abilities may be developed via immersive protocols, which will enable instructors to focus on the development of other vital road safety skills in novice cyclists, such as decision making. Furthermore, nationwide rollout of immersive training may increase the accessibility, and therefore inclusivity, of the Bikeability provision for both children and adults.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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