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Can immersive training complement on-road cycle training for children? Two intervention studies in urban and rural UK communities

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ABSTRACT

Introduction: Cyclists are frequent casualties in road traffic collisions; failure to look is a contributory factor. Recent research shows that immersive training may improve children's performance, including their observational skills, when cycling on roads. However, robust data in this regard are scarce.
Methods: In two related studies, we collected data from 95 children aged 9–11 years across two different UK locations – a cycling-supportive city and a rural town – to ascertain the effects of immersive cycle training on their cycling attitudes and confidence, their situation awareness, and on-road performance. In the urban study we employed a traditional control group design (immersive intervention vs. control); in the rural study, we compared two immersive interventions (with verbal prompts vs. without). At pre-intervention, post-intervention, and 4–6 weeks later (retention), the children reported their attitudes and confidence and completed video-based situation awareness tests (SATs) and on-road cycling assessments (ORCAs). Changes in parental confidence and attitudes were also recorded.
Findings: In both studies, ORCA performance improved pre-to-post-intervention, irrespective of group. SATs scores did not improve but were somewhat correlated with ORCA performance. Although the children's cycling attitudes did not change, their confidence increased post-intervention. Parents' confidence in their child's ability to cycle increased significantly from pre-intervention to follow-up, after watching POV footage recorded during their child's retention phase ORCA.
Conclusions: The contribution of immersive training to young children's on-road cycling ability is indeterminate. We tentatively suggest that a combination of independent on-road, immersive, and video-based cycling experiences may improve this ability and consequently increase parental confidence.

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1. Introduction

Cycling can significantly increase our daily physical activity levels (Salway et al., 2019) and therefore confer multiple benefits for our physical and mental health (Bell et al., 2019; Cheng et al., 2020; Dkaidek et al., 2023; Hoare et al., 2016). However, it is not a popular mode of travel for short journeys in the UK (Department for Transport, 2024a). This is partly due to safety concerns (Pearson et al., 2023; Salmon et al., 2007), including those of parents (Wilson et al., 2018; Woldeamanuel, 2016); the latter is particularly relevant, because parents' cycling-related attitudes and behaviour strongly influence their children's cycling behaviour (Bishop et al., 2024). Unfortunately, such concerns are supported by scientific research: cyclists are overrepresented casualties in road collision statistics, globally (Björnstig et al., 2017; Bouaoun et al., 2015; de Lapparent, 2005; Isaksson-Hellman and Werneke, 2017; O'Hern and Oxley, 2018).

In 2023, 4029 pedal cyclists were killed or seriously injured on Britain's roads – an average of 11 cyclists per day; almost a third of these casualties were children and young people (Department for Transport, 2024b). Moreover, almost two-thirds of all fatalities and serious injuries involving pedal cyclists occurred at junctions (T junctions, staggered junctions, roundabouts and crossroads). The two most common contributory factors were *driver or rider failure to look properly* and *driver or rider failure to judge the other person's path or speed* (Department for Transport, 2024b). Consistent with these national data, empirical reports of collisions and traffic violations involving cyclists frequently implicate misallocation of attention (Bishop et al., 2023a; Møller et al., 2021; Salmon et al., 2022; Useche et al., 2018; Vanparijs et al., 2016). Hence, educational programmes that improve young cyclists' ability to allocate their attention effectively may increase their safety and, consequently, their propensity to cycle short journeys.

Cycling education programmes are still a rarity in most developed countries, with some notable exceptions such as the *Nationaal VVN Verkeersexamen* in The Netherlands (https://examen.vvn.nl/) *AusBike* in Australia (https://ausbike.au/) and *BikeReady* in New Zealand (https://www.bikeready.govt.nz/); all of them are aimed at young children and are aligned with educational curricula accordingly. The UK's *Bikeability* programme (https://www.bikeability.org.uk), which is delivered to over half a million children per year, is the largest road safety education programme in the world that is owned and funded by Government. Bikeability Level 2 training is delivered to 9-11-year-olds on roads and focuses on the four key skills of the UK National Standard for Cycle Training: making good and frequent observations (hereafter, *observation*), communicating intentions clearly to other road users (*communication*), choosing and maintaining the most suitable riding positions (*position*), and prioritising road use, particularly at junctions (*priorities*); observation is a prerequisite for the other three skills. Accordingly, recent evidence suggests that Bikeability training may reduce the number of road users killed or seriously injured (KSIs) on UK roads (Transport Research Laboratory, 2024). Specifically, higher Bikeability Level 2 training delivery rates were associated with *fewer* KSIs.

Common to all cycle education programmes is the development of riders' hazard perception skills and their *situation awareness*. Situation awareness has been described as an individual's perception of elements within time and space, their comprehension of the meaning of those elements, and their projection of their future state (Endsley, 1995). It has been investigated extensively in driving (e.g., Baumann and Krems, 2007; Endsley, 2020; Gugerty, 2011; Underwood et al., 2013) and to a lesser extent in cycling (e.g., Beanland and Hansen, 2017; Bishop et al., 2022a; Bishop et al., 2023b; Lehtonen et al., 2017; Salmon et al., 2013). Whilst hazard perception can be determined by overt responses to potential hazards, or where they might appear (e.g., a mouse click on an oncoming vehicle, in a screen-based assessment; Moran et al., 2019), situation awareness tests often comprise elements that are not hazardous per se, but might influence whether a hazard might appear, and/or the severity of the hazard. For example, a cyclist's situation awareness may include their *perception* of an impending speed limit increase (e.g., from reading a sign), their *comprehension* of what this means for them (e.g., other vehicles will be moving faster), then their ability to anticipate what they must do next (e.g., to expect more frequent overtaking; *projection*) (Bishop et al., 2022a, 2023b). There is evidence that younger/less experienced cyclists' situation awareness and hazard perception are inferior to that of older/more experienced ones (De Geus et al., 2020; Lehtonen et al., 2017; Meir and Dagan, 2020; Melin et al., 2018; Sun et al., 2023; Vansteenkiste et al., 2016; Vansteenkiste et al., 2017; Zeuwts et al., 2017a). However, research in the last decade has shown that young cyclists' situation awareness and hazard perception can be improved with video-based training (e.g., Bishop et al., 2022a; Zeuwts et al., 2017b), although the findings have been mixed (e.g., Lehtonen et al., 2017; Kovácsová et al., 2020) and there is limited evidence for *positive transfer* to real world cycling behaviour from such interventions, which is problematic when we consider the severe consequences of *failure to look properly* (Department for Transport, 2024b).

Real-world behaviours such as head turning are often not included in video-based interventions, despite their importance for cycling safety – especially around junctions (O'Hern et al., 2017). Bishop et al. (2022a) addressed this shortcoming by creating an immersive training protocol that required participants to turn their heads frequently. In a mixed design, children aged 10–12 years who had completed Bikeability Level 2 training were randomly assigned to an intervention or control group, matched by cycling experience, age and gender. Qualified Bikeability instructors assessed the children's on-road cycling ability vis-à-vis the four key skills in post-test and retention phases, and a video-based situation awareness test (SAT) was used to assess their situation awareness and hazard perception. For the immersive intervention, participants sat on a stationary bike surrounded by three video screens depicting cyclist POV footage. They viewed an instruction video, designed to develop their understanding of the relationship between eye movements and attention, followed by a series of five virtual routes in which they heard prerecorded prompts and questions relating to events and key required behaviours, such as looking behind to check for other road users. Their findings indicated that the intervention elicited head turning and gaze behaviours like those required in the real world, such as a higher frequency of head turns at T-junctions and rearward looking – both vital safety-related behaviours. Furthermore, in both the post- and retention test, the intervention group outperformed the control group for each of the four key skills in the on-road assessment. However, there were no significant improvements in the intervention group's situation awareness relative to the control group, as assessed in post-test and retention SATs.

This lack of correspondence between on-road cycling performance and video-based SATs performance may be more reflective of the insensitivity of the latter, rather than an absence of between-group differences in situation awareness – a notion that warrants closer scrutiny.

Although Bishop et al.'s (2022a) intervention was seemingly effective in several respects, the authors noted that the lack of portability of their experimental setup was a potential limitation, one that might limit wider rollout of immersive training within local communities. To address this shortcoming, Bishop and colleagues (2023b) delivered a brief (i.e., 10-min) gamified immersive cycle training intervention via head-mounted display to two groups of 11-14-year-olds; One group, the *explicit learning group*, heard prerecorded instructions during the intervention designed to increase their adaptive looking behaviour (e.g., "Are there vehicles approaching behind you?"), and the other group, the *implicit learning group*, did not receive such prompts. In an automated protocol, participants in both groups could obtain 'reward points' for looking in appropriate locations at the right times, such as looking into a side road ahead to see whether other road users are about to emerge; they received auditory feedback for doing so. The authors examined changes in participants' looking behaviour over the course of the intervention – i.e., in-task learning – as well as changes in their situation awareness, using Bishop et al.'s (2022a) SATs. They also recorded participants' confidence and attitudes regarding cycling on roads before and after the 10-min intervention. In the early stages of the intervention, the explicit learning group accrued significantly more reward points than the implicit learning group, indicating the initial effectiveness of the instructions. However, the implicit learners caught up with their explicit learning counterparts by the midway point of the intervention – possibly evidence that the auditory feedback (i.e., reward sounds) was sufficient to entrain appropriate observational behaviours such as rearward looking. Additionally, the intervention increased the children's confidence for cycling on roads, and this increase was positively correlated with their performance in the intervention. However, Bishop et al. (2023b) did not assess the children's on-road cycling performance. Hence, there is a need to investigate the effects of a more portable and gamified immersive training protocol, with or without explicit instructions, on children's ability to cycle safely on roads, as well as their confidence to do so.

1.1. *The present studies: aims, objectives and hypotheses*

Laboratory studies of video-based cycle training interventions (e.g., Bishop et al., 2022a; Lehtonen et al., 2017; Kovácsová et al., 2020) have provided mixed evidence for improvements in looking behaviour and situation awareness – and most have not investigated transfer of learning from the laboratory to the real world, with some exceptions (e.g., Bishop et al., 2022a); this must be addressed. Also, if we are to maximise the impact of such interventions, it is important to consider how they can be delivered by practitioners such as cycle training professionals, within their local communities (Bishop et al., 2023b).

Therefore, the main aim of the present studies was to determine whether immersive training, delivered by Bikeability instructors, could complement young children's Bikeability Level 2 training, notably by improving their ability to cycle on roads in accordance with the four key skills. We also aimed to establish whether the training could increase the children's situation awareness, and their self-reported confidence and attitudes regarding cycling on roads, as assessed via a combination of video-based SATs and self-report data.

Additional objectives were as follows: (i) to determine whether built-in verbal prompts and auditory rewards designed to increase looking behaviour and situation awareness during immersive training could further enhance children's on-road cycling performance and situation awareness; (ii) to explore the relationship between the children's performance in video-based SATs and their on-road cycling ability (prior research suggests there is no relationship [Bishop et al., 2022a]); and (iii) to examine whether increasing the parent's awareness of their child's improved on-road cycling performance could increase their confidence in their children's ability to cycle on roads.

Consequently, we made the following predictions: (1) that children in an immersive training intervention group would outperform those in a control group who did not receive the training, in on-road cycling assessments (ORCAs) and video-based situation awareness tests (SATs); (2) that a group who received prerecorded prompts in the immersive intervention would outperform those who did not receive the prompts, in ORCAs and SATs; and (3) that children's and parents' attitudes and confidence regarding cycling on roads would improve over the study duration, for all intervention groups.

2. Methods

2.1. *Study locations, study design and participants*

2.1.1. *Study locations*

The study was advertised to Bikeability cycle training providers nationwide. Those with appetite and capacity for running the study were invited to submit an expression of interest. On this basis, five training providers were identified, three of whom were ultimately unable to fulfil their obligation. Two Bikeability cycle training providers, ultimately supported participant recruitment and delivery of the study.

Accordingly, data relating to two intervention studies were collected from 95 children across two different UK locations – one classified as *Urban: City and town* (hereafter, *'urban location'*) and one classified as *Rural: Town and Fringe in a sparse setting* (hereafter, *'rural location'*) based on UK government classifications (https://www.gov.uk/government/collections/rural-urban-classification). Data collection in the urban location occurred near to the training provider's head offices, whereas data collection in the rural location was undertaken in two local primary schools.

2.1.2. Study design

Fig. 1 provides an overview of the study design, which was almost identical for both locations; only the comparison groups differed. Specifically, and in line with our first stated aim, in the urban location we compared the effects of an immersive cycle training intervention (Intervention group) on Bikeability Level 2 cycle training graduates' on-road cycling performance, situation awareness, and self-reported confidence and attitudes regarding cycling on roads. And consistent with our first additional objective, in the rural location we examined the effect of providing verbal guidance and auditory rewards during immersive cycle training (*explicit learning*), versus an immersive protocol comprising minimal auditory information (prompts to highlight upcoming turns and manoeuvres; *implicit learning*).

For both studies, a mixed design was employed in which participants' performance in on-road cycling assessments (ORCAs) and video-based situation awareness tests (SATs), cycling attitudes and confidence, were recorded in three phases (*Pre-Intervention*, *Post-Intervention*, and *Retention*) before and after an immersive cycle training intervention or Control group equivalent (urban location only; see Section 2.1.3.2). All data collection was overseen by four Bikeability cycling instructors (one urban, three rural), except for the surveys at Pre-Intervention and Follow-Up phases, which participants completed online in a location of their choosing. Most other data were collected in person at the children's schools or other dedicated venue (self-report, SATs and intervention), and on local roads (ORCAs only).

2.1.3. Participants

2.1.3.1. Sample size power analysis. The primary dependent variable of interest in both studies was on-road cycling i.e., ORCA) performance. Although Bishop et al. (2022a) found a very large effect ($\eta_p^2 = 0.42$) for between-group differences in this measure, they did not assess the children's on-road performance before the intervention, so this effect size may have been inflated accordingly. So, using the statistical power analysis freeware G*Power 3 (Faul et al., 2007) we estimated a moderate effect size, but with statistical power set at 0.95 and criterion alpha set at 0.05. The total required sample size in each study was 44 participants – 22 in each group. We aimed to recruit 50 children in each location, 25 per group.

2.1.3.2. Urban location. The urban study comprised 44 children (13 female, 31 male) aged 9–11 years (M = 10.4 yrs, SD = 0.7 yrs) and their parents/carers (*hereafter 'parents'*). The children were allocated either to an Intervention group (immersive cycle training; $n = 23$) or a Control group ($n = 21$), with matching across groups for gender and cycling experience (years of cycling unaided, hours per month of cycling; see Section 3.1). These children were predominantly of White UK ethnicity ($n = 28$), and the remainder were Chinese (4), Indian (1), and Pakistani (1); five stated 'Other' but did not specify, four preferred not to say, and one participant's demographic data were missing. Four children reported learning differences, five reported an impairment but did not specify. Their self-reported moderate-to-vigorous physical activity (MVPA) per week ranged from 2 h to 50 h (M = 17.3 h, SD = 11.2 h); one outlying value (140 h; >3.29 SDs) was excluded.

2.1.3.3. Rural location. The rural study comprised 51 children (25 female, 26 male) aged 9–10 years (M = 9.8 yrs, SD = 0.4 yrs) and their parents. The children were allocated to one of two different immersive cycle training intervention groups: one in which riders heard prerecorded prompts which directed their attention and actions (see Section 2.2.3 for more details; *Explicit Learning group*; n =

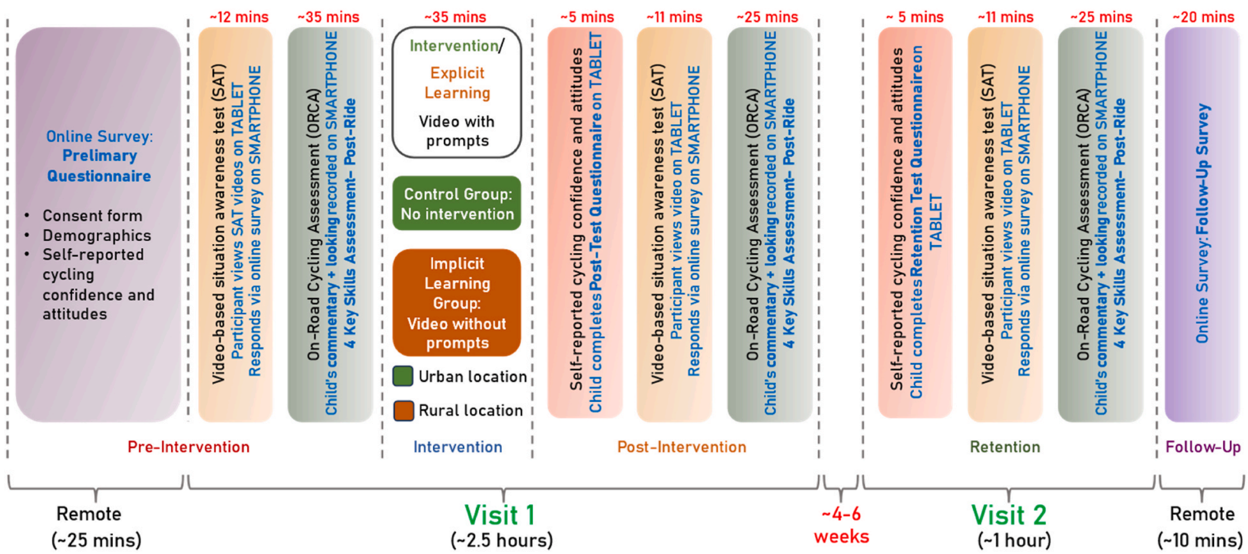

Fig. 1. Study design.

25; cf. Bishop et al., 2023b) or a group that received no prompts (*Implicit Learning group*; n = 26). These groups were also matched for gender and cycling experiences (see Section 3.1). These children were almost exclusively of White UK ethnicity (*n* = 50), and one was Chinese (1). Four of them reported learning differences, but no mental or physical impairments were reported. Their reported weekly MVPA ranged from 2 h to 60 h (*M* = 17.6 h, *SD* = 12.3 h).

2.1.3.4. Cycle ownership, cycling ability & behaviour. Across both locations, all the children were able to cycle, had completed Bikeability Level 2 training (a prerequisite for study participation), and owned their own cycle. Table 1 illustrates the cycling experience and habitual cycle behaviour of the children and their parents, by location. The children's cycling behaviour was analysed to establish whether between-location and/or between-group differences existed prior to the children's participation in the study (see Sections 2.3.1 and 3.1). Full cycling behaviour data can be found in Supplementary Materials.

2.2. Measures, materials and procedures

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.

To facilitate data collection across the phases of the study, each child participant was assigned a unique participant ID, which was inputted by the participant, their parent, or their designated instructor, at all stages of data collection.

2.2.1. Preliminary questionnaire (Remote)

Prior to the child's first visit to the testing venue, the children (*hereafter, 'riders'; the preferred term in Bikeability training*) and their parents completed a questionnaire on the JISC online survey platform (JISC, 2024). Riders and parents provided demographic characteristics (age, gender, ethnicity, mental and physical impairments), their activity levels (average hours per week of MVPA; see Supplementary Materials for raw data) and information relating to their cycle access, cycling ability and training status, and cycling behaviour (hours of cycling per month; *cycle journeys < 5 miles*, *journeys > 5 miles*, *cycling for fun*, and *cycling competitively* in the preceding four weeks).

Riders and their parents also indicated their attitudes towards cycling and confidence for cycling on roads via self-report measures based on ones used previously (Bishop et al., 2022a, 2023b). To indicate their attitude toward cycling, the riders and their parents identified the extent of their agreement with several statements, prefaced by the stem, "Cycling on roads is …": *tiring*, *efficient*, *stressful*, *enjoyable*, *difficult*, *convenient*, *boring*, *relaxing*, and *safe*; they did so via a scale ranging from 1 (*Strongly Disagree*) to 5 (*Strongly Agree*). The riders reported their confidence for cycling on roads via a series of items relating to their *Awareness* (10 items), *Decisions* (11 items) and *Control* of their movements, including those of their cycle (7 items). All items were prefaced with the stem, "How confident are you in your …". Example items include "… awareness of when and how often to look behind?" (*Awareness*), "… ability to communicate appropriately using hand signals?" (*Decisions*) and "… ability to look over your right shoulder?" (*Control*). Additionally, parents answered the questions, "How confident are you in YOUR ability to cycle on roads?" and "How confident are you in YOUR CHILD'S ability to cycle on roads?" on a scale ranging from 1 (Not at all confident) to 6 (Very confident). They were also invited to provide an explanation for their ratings (see Supplementary Materials).

Riders were booked in for Visit 1 within four weeks of their parent submitting the Pre-Intervention Questionnaire. Visits 1 (pre, post) and 2 (retention) were an average of 46.3 days apart (SD = 19.6 days) in the urban location, and an average of 40.2 days apart (SD = 7.2 days) in the rural location.

2.2.2. Pre-Intervention (Visit 1)

2.2.2.1. Situation Awareness Tests (SATs). Footage was filmed by the first author on major and minor UK roads, from a young cyclist's perspective, using a 170-degree field-of-view camera (GoPro Hero 8; GoPro Inc. CA) mounted on the handlebar stem of an all-terrain

Table 1
Cycling experience and behaviour of children and parents, by location.

		Children		Parents	
		Urban*	Rural	Urban*	Rural
Years of Cycling Unaided [Mean (SD)]		5.6 (1.5)	4.8 (1.3)	33.4 (13.6)	33.0 (10.9)
Cycling frequency (hrs/month; [Mean (SD)]		10.0 (15.6)	8.9 (8.5)	14.4 (31.9)	4.5 (7.1)
Journeys <5 miles:	Never	0	10	5	18
Rarely		1	3	1	5
Sometimes		12	17	7	17
Frequently		30	21	30	11
Journeys ≥5 miles:	Never	11	23	10	24
Rarely		23	13	15	11
Sometimes		6	12	13	12
Frequently		3	3	5	4

Note. *n = 43 due to missing data from one participant.

bicycle; cycling speed was maintained at 8–10 mph, and riding positions conformed to the UK National Standard for cycle training (Department for Transport and Driver & Vehicle Standards Agency, 2019) and the UK Highway Code (Department for Transport and Driver & Vehicle Standards Agency, 2023). The video footage was edited in Adobe Premiere Pro (Adobe, San Jose, CA) to create a pool of 139 viable clips. All clips were reviewed by the first and second authors to generate a final list of 72 clips which were distributed evenly across three different SAT versions (SAT A, SAT B, SAT C) such that each version comprised 24 clips of similar challenge levels – specifically, those rated *low*, *moderate*, or *high challenge* were equally represented in each version; they also included clips used in previous studies (Bishop et al., 2022a, 2023b). Each SAT version comprised eight clips that assessed the riders' *perception* of elements in the video scenarios (e.g., presence of an oncoming car), eight to determine their *comprehension* of the meaning of those elements (e.g., that they should give way to the driver of the car), and eight to gauge the riders' ability to anticipate what might happen next (e.g., that the car might move towards them through a road narrowing; *projection*) – in other words, their *situation awareness* (Endsley, 1995). Each video clip was occluded, without a freezeframe (cf. Crundall, 2016) and followed by a multiple-choice question; they also heard a recorded voiceover of the question. Example questions include "Did the oncoming car cross the centre line?" (Yes/No; *Perception*), "Which position were you in when the video ended?" (Primary/Secondary/Tertiary; *Comprehension*) and "You want to go straight ahead at the roundabout. What will you do next?" (Stop at the Give Way lines/Check for vehicles behind me/Proceed with caution/checking for vehicles to my right; *Projection*).

A different situation awareness test version (SAT A, SAT B, or SAT C) was used in each phase. The order of these versions across the three phases of the study was counterbalanced across participants. Riders viewed the SAT on an Android tablet device and provided responses via a JISC online survey displayed in the browser of an Android tablet or smartphone device. They listened to the real-world video ambient sounds (traffic noise etc.) and each of the 24 questions via headphones (see Fig. 2). Each SAT took approximately 10 min to complete.

2.2.2.2. On-road cycling assessments (ORCAs). Fig. 3 shows the routes used in each location. For each location, a route approximately 2 miles in length was determined and agreed by the Bikeability training providers and the first author. The routes incorporated major and minor roads, and all four major types of turn performed during Bikeability Level 2 training (*left in*, *right in*, *left out*, *right out*). Each rider completed the ORCAs on the same route in each phase. Two routes were used in the rural location because the instructors delivered the training within two local schools (*n*'s = 25 & 26), located 4.5 miles apart, with national speed limit roads (60 mph; not used during Bikeability Level 2 training) in between, so it was deemed unfeasible for riders to travel between the schools; hence, the routes were local to the schools. All rural instructors conducted ORCAs on both routes, i.e., for riders from each school. All ORCAs in the urban location were conducted on a single route, outside of school hours, and it was the parents' responsibility to transport their

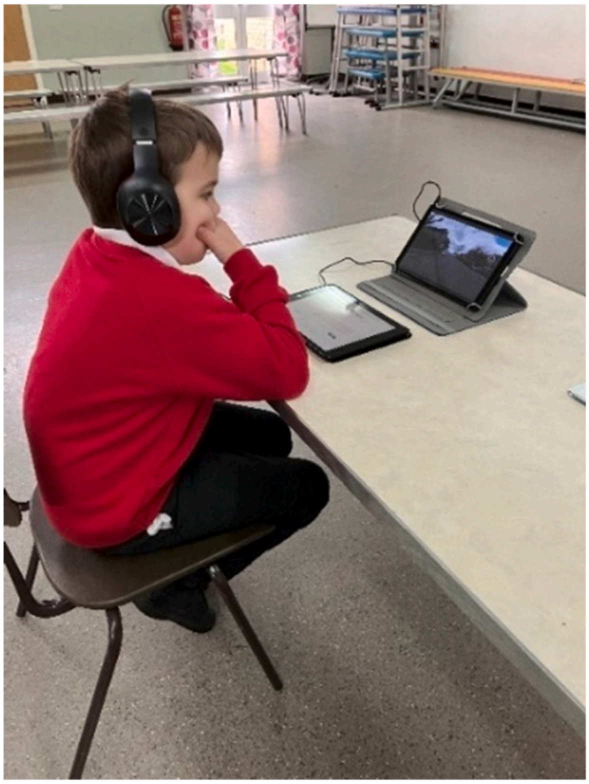

Fig. 2. Participant completing a situation awareness test (SAT).

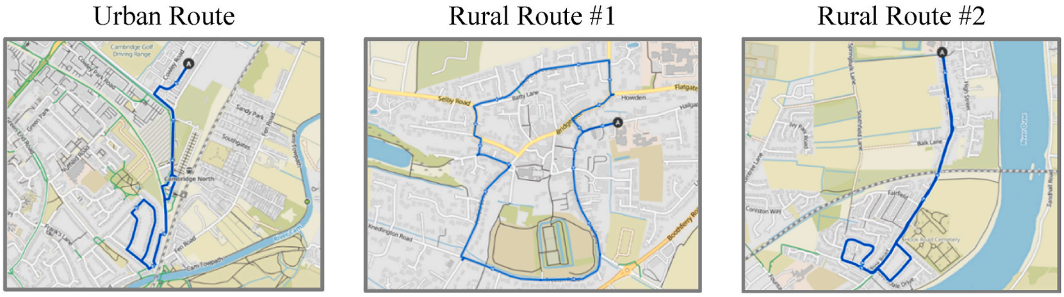

Fig. 3. ORCA routes – overview.

children to the start location.

Fig. 4 shows a rider and instructor completing an ORCA. Participants used their own cycles, and the rider wore appropriate clothing and a bespoke kitemarked cycle helmet. A smartphone was mounted in landscape orientation on the helmet such that its primary camera faced forward, to record video and audio for subsequent use.

The rider also wore a high visibility gilet with a rear pocket containing a mobile phone, to which a set of motorcycle headphones with in-line microphone were connected; theses were mounted on straps attaches to the sides of the helmet. The rider was asked by the instructor to provide a running commentary of their observations and thoughts as they cycled, to illustrate their situation awareness. The instructor cycled a few metres behind the rider and only communicated with them minimally (e.g., to indicate upcoming turns); they were also asked to prompt the rider to keep talking, where possible. Video footage was automatically uploaded to secure cloud storage for subsequent analysis, once the smartphone was being charged and was connected to a verified Wi-Fi network. Two examples of POV video footage captured via the smartphone cameras can be found in Supplementary Materials (NB: rider audio removed for data protection reasons).

After the rider had completed the route, the instructor completed a bespoke questionnaire (*Four Key Skills Questionnaire [4KSQ]*; cf. Bishop et al., 2022a) in which they indicated how often the rider had demonstrated each of the four key skills (*Observation*, *Communication*, *Position*, *Priorities*), with response scales ranging from 1 (*Never*) to 4 (*Always*); they could also indicate when there was no opportunity to demonstrate a Key Skill. Example items are "The rider looked over their left shoulder, when required" (*Observation*), "The rider attempted to make eye contact with a road user approaching from the rear" (*Communication*), "The rider adopted the Primary Position when required" (*Position*) and "The rider judged road user and pedestrian priorities correctly when negotiating junctions" (*Priorities*). They also rated, and could comment on, the environmental conditions under which the ORCA took place – specifically, whether traffic, sunshine brightness (i.e., the extent to which it impaired vision), rain, snow, hail, wind, disruption of road surface, and dampness of road surface, were *Heavy* (scored 1), *Moderate* (2), *Light* (3), or *None* (4). Instructors' elaborations on their ORCA observations are available in Supplementary Materials.

2.2.3. Intervention (Visit 1)

Riders sat on a 14-inch all-terrain bicycle, the rear wheel of which was mounted on a cycle trainer; the front wheel was mounted on a riser. The handlebar stem was loosened such that the rider could turn the handlebars. Throughout the intervention, they wore an HTC Vive ProEye (Taoyuan City, Taiwan) head-mounted device (Fig. 5), which was used to display 360-degree young rider point-of-view video footage filmed on urban UK roads (See Fig. 6; cf. Bishop et al., 2023b).

Fig. 4. Rider and instructor completing an on-road cycling assessment (ORCA).

In a 27-min intervention comprising three different virtual routes each lasting ~8.5 min, riders in all groups across both studies heard real-world video ambient sounds, as well as prerecorded prompts to notify them of upcoming turns, so that they could perform the looking and signalling routines taught during their Bikeability training.

Riders in the Intervention group (*urban location*) and Explicit Learning group (*rural location*) also heard prerecorded prompts designed to promote adaptive looking behaviour and situation awareness; for example, "Is there a vehicle approaching behind you?" Over the course of the three virtual routes, the frequency of prompts decreased, to promote rider autonomy (see Intervention SCRIPT.docx). Riders in these groups also heard reward sounds if they looked in appropriate locations (e.g., into side roads) at the right times to gamify the intervention. When they fixated on low-challenge targets, participants heard a two-tone chime sound; 1 point was awarded for fixation on these targets. When they fixated on intermediate-challenge targets, participants heard a bell sound and obtained 5 points. Fixation on high-challenge targets elicited a cash register sound and obtained 10 points.

Riders in the Implicit Learning group (*rural location)* did not hear any of the prerecorded prompts to promote looking behaviours and situation awareness, and they did not hear reward sounds when they obtained them, but they were awarded points when fixating on targets (cf. Bishop et al., 2023b).

Throughout each of the three virtual routes, the instructor completed a bespoke checklist to denote the extent to which the rider performed such routines – specifically, for two of the four key skills of Bikeability training: their *observation* (checking over their shoulders) and *communication* (hand signalling). The instructors answered items such as "Which elements of a right-hand turn routine did they perform?", by selecting all elements they observed from a list; for example, 'Looked over right shoulder', 'Signalled right', 'Second look over right shoulder' and 'None'.

Control group participants (urban location only) sat for an equivalent period and were allowed to read during this time but were not allowed to look at any smartphone, tablet or other screen-based devices. They were offered the opportunity to complete the intervention after they had finished their participation in the study. All of them accepted the opportunity.

2.2.4. *Post-Intervention (Visit 1)*

Immediately after the intervention (or seated rest equivalent) the rider reported their attitudes towards cycling and their confidence vis-à-vis cycling on roads on the same items used in the Pre-Intervention Questionnaire, again via a JISC online survey, viewed on a tablet device. The rider then completed a different SAT version before completing another ORCA on the same route.

2.2.5. *Retention (Visit 2)*

Four to six weeks after Visit 1, the rider returned to the testing location to (a) report their attitudes towards cycling and their confidence for cycling on roads as above, (b) complete the third and final SAT version, then (c) undertake one final ORCA. The video captured from the helmet-mounted smartphone in the ORCA was sent via secure cloud storage to each rider's parent.

2.2.6. *Follow-up survey*

In a follow-up survey emailed to parents immediately after their children had completed their participation in the study, the riders rated the *interestingness*, *usefulness* and *immersiveness* of the intervention and could provide textual explanations for their ratings if they wanted to. They also rated the interestingness and usefulness of the SATs and ORCAs and could also explain those ratings. All ratings were made on a scale ranging from 0 (zero; "Not at all …") to 10 ("Extremely …").

Riders and parents reported their attitudes towards cycling again. Parents also reported their confidence in their own ability to cycle on roads, and in their child's ability to do so, one more time – after they had viewed their child's POV footage obtained at the Retention phase. All participants were invited to provide qualitative data to elaborate on their ratings (see Supplementary Materials).

Fig. 5. Immersive intervention setup.

Fig. 6. Rider point-of-view footage.

2.3. Data analysis

All data were screened for outliers (values ± 3 SD) and non-normality prior to analysis. For repeated measures analyses, Mauchly's Test of Sphericity was used to determine whether the assumption of sphericity had been violated and Greenhouse-Geisser adjustment was applied where violations arose. Comparisons were made between groups, and over the various phases of the project, in each location separately. Partial eta squared (η_p^2) is reported as the effect size measure for ANOVAs and MANOVAs; Cohen's d is reported for t tests. The alpha level for significance was set at $p < .05$ for all comparisons, and 95 % confidence intervals (CIs) are reported where applicable. All analyses were conducted using SPSS software (version 29.0.1.0; SPSS Inc., Chicago IL). Descriptive observations were also made between locations in the Discussion section, where relevant.

2.3.1. Rider cycling experience and behaviour

For each location, independent samples t tests were performed to establish whether between-group differences existed in riders' years of cycling unaided and hours of cycling per month prior to their participation in the study. Also, mixed MANOVAs (Phase [3] x Group [2]) were used, for each location, to determine whether changes in the frequency of *journeys less than five miles*, *journeys greater than 5 miles*, *cycling for fun*, and *cycling competitively* within the previous four weeks changed across Pre-Intervention, Retention and Follow-up phases, by Group – i.e., within-study changes in the riders' cycling behaviour.

2.3.2. ORCA performance (Four Key Skills Questionnaire [4KSQ])

Given the interdependence of the four key skills (*observation*, *communication*, *position* and *priorities*), 4KSQ scores were combined to create one overall ORCA performance score, analysed in two separate 2 (Group; *Intervention* vs. *Control, Prompts* vs. *No Prompts*) x 3 (Phase; *Pre-Intervention*, *Post-Intervention*, *Retention*) mixed-design ANOVAs, one for each location.

2.3.3. SATs

Participants' scores were converted into percentage values and analysed in two separate 2 (Group) x 3 (Phase) mixed-design ANOVAs, one for each location. The three SAT versions (SAT A, SAT B, SAT C) were also assessed via one-way ANOVA to determine the variability, if any, in the level of challenge they presented to riders. To fulfil our second additional objective (see Section 1.1), zero-order correlations were conducted to explore potential relationships between riders' SAT scores and their ORCA performance (4KSQ scores).

2.3.4. Rider and Parent attitudes

Ratings were aggregated to create *positive attitudes* and *negative attitudes* scores. Rider data were analysed in two 2 separate (Group) x 3 (Phase) mixed-design MANOVAs, one for each location. Parent data were analysed in two separate 2 (Group) x 2 (Phase; *Pre-Intervention*, *Follow-Up*) mixed-design MANOVA, also one for each location.

2.3.5. Rider confidence

Riders' self-reported ratings for their confidence in their *Awareness*, *Decisions* and *Control* were analysed in two separate 2 (Group) x 3 (Phase) mixed-design MANOVAs, one for each location.

Because accomplishments are a known antecedent of confidence (Anstiss et al., 2020), we made a retrospective decision to explore potential relationships between riders' 4KSQ scores and their confidence, for each phase, so that we could better understand the origins of riders' confidence judgements. Hence, we performed zero-order correlations for these measures.

2.3.6. Parental confidence

Parents' ratings, at Pre-Intervention and Follow-up, of their confidence in *their ability to cycle on roads*, and *their child's ability to cycle* *on roads* were analysed using two repeated measures MANOVAs, one for each location.

2.3.7. Supplementary analyses

We conducted supplementary additional analyses, ones that were not directly related to our main aims and would have rendered this manuscript unwieldy if they were to be included. Nonetheless, because they are useful for illuminating and interpreting our key findings, these analyses are provided in SUPPLEMENTARY ANALYSES.docx. These analyses are referred to in the Discussion, using the prefix *SA#*, where applicable.

3. Results

One outlying datapoint was removed from self-reported MVPA data (see Section 2.1.2.2); there were no other outliers in the data. There were some minor violations of normality, but these were seemingly due to random, not systematic, fluctuations in the data – for example, interindividual variability in ORCA performance – so parametric statistical tests were used. Mauchly's Test of Sphericity showed violations for ORCA performance (urban rider data only) and rider confidence (urban and rural rider data; Awareness, Decisions, and Control), and so Greenhouse-Geisser corrections were applied.

3.1. Rider cycling experience and behaviour

3.1.1. Cycling experience, by group

There were no pre-existing differences between Intervention and Control groups (urban location) or Prompts and Implicit Learning groups (rural location), in riders' years of cycling experience, nor in the hours of cycling per month they accrued, $p > .05$.

3.1.2. Within-study cycling behaviour

In both locations, there were no differences across Phase or Group in terms of riders' cycling behaviour during the study (frequency of *journeys less than five miles*, *journeys greater than 5 miles*, *cycling for fun*, and *cycling competitively* in the previous four weeks), for both locations, $p > .05$.

3.2. ORCA performance (Four Key Skills Questionnaire; 4KSQ)

3.2.1. Urban location

Fig. 7 shows urban riders' mean 4KSQ scores, by Group and Phase.

There was no Phase by Group interaction. However, there was a main effect of Phase, $F(1.54,57.29) = 48.85$, $\eta_p^2 = 0.57$, $p < 0.001$. Bonferroni pairwise comparisons showed that riders' 4KSQ scores increased from Pre-Intervention ($M = 2.65$, $SD = 0.41$) to Post-Intervention ($M = 2.90$, $SD = 0.36$), $p < .001$, 95 % CI = 0.15–0.35, and from Post-Intervention to Retention ($M = 3.21$, $SD =$

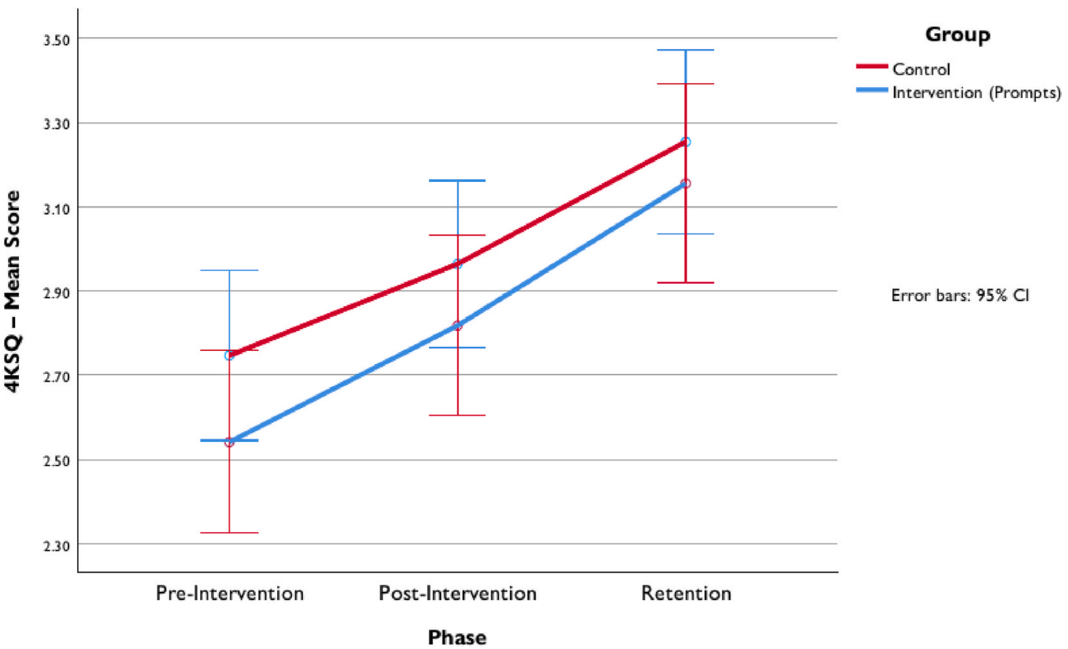

Fig. 7. 4KSQ score, by group and phase – urban location.

0.48), $p < .001$, 95 % CI = 0.41–0.72).

3.2.2. Rural location

Fig. 8 shows rural riders' mean 4KSQ scores, by Group and Phase. There was no Phase by Group interaction, nor a main effect of Phase, all p's > 0.05.

3.3. SATs

3.3.1. Urban location

There were no main effects of Phase or Group, nor an interaction effect, all p's > 0.05.

3.3.2. Rural location

There were no main effects of Phase or Group, nor an interaction effect, all p's > 0.05.

3.3.3. SATs – 4KSQ correlations

Riders' performance in the SATs correlated somewhat with their overall performance in the ORCAs, $r(277) = 0.166$, $p = .003$. Table 2 shows the correlations by Location and Phase, which suggest that this correlation was driven primarily by all riders' Retention phase scores and urban riders' Pre-Intervention scores.

3.4. Rider and parent attitudes

There was no effect of Phase or Group, nor their interaction, on the riders' or their parents' attitudes towards cycling on roads, positive (*efficient*, *enjoyable*, *convenient*, *relaxing*, *safe*) or negative (*tiring*, *stressful*, *difficult*, *boring*), for both locations, $p > .05$.

3.5. Rider confidence

3.5.1. Urban location

There was no Phase by Group interaction. However, there was a significant multivariate effect of Phase, $F(6,156) = 3.03$, Pillai's Trace = 0.21, $\eta_p^2 = 0.10$, $p = 0.008$.

Univariate tests revealed significant effects of Phase on riders' confidence in their *Awareness*, $F(1.42,250.16) = 4.60$, $p = .02$, $\eta_p^2 = 0.10$, and *Control*, $F(1.47,148.39) = 6.62$, $p = .006$, $\eta_p^2 = 0.14$. Bonferroni pairwise comparisons showed that riders' confidence in their *Awareness* increased from Pre-Intervention ($M = 44.16$, $SD = 9.24$) to Post-Intervention ($M = 47.61$, $SD = 6.11$), $p = .009$, 95 % CI = 0.65–5.71; and their confidence in their *Control* also increased from Pre-Intervention ($M = 33.93$, $SD = 5.09$) to Post-Intervention ($M =$

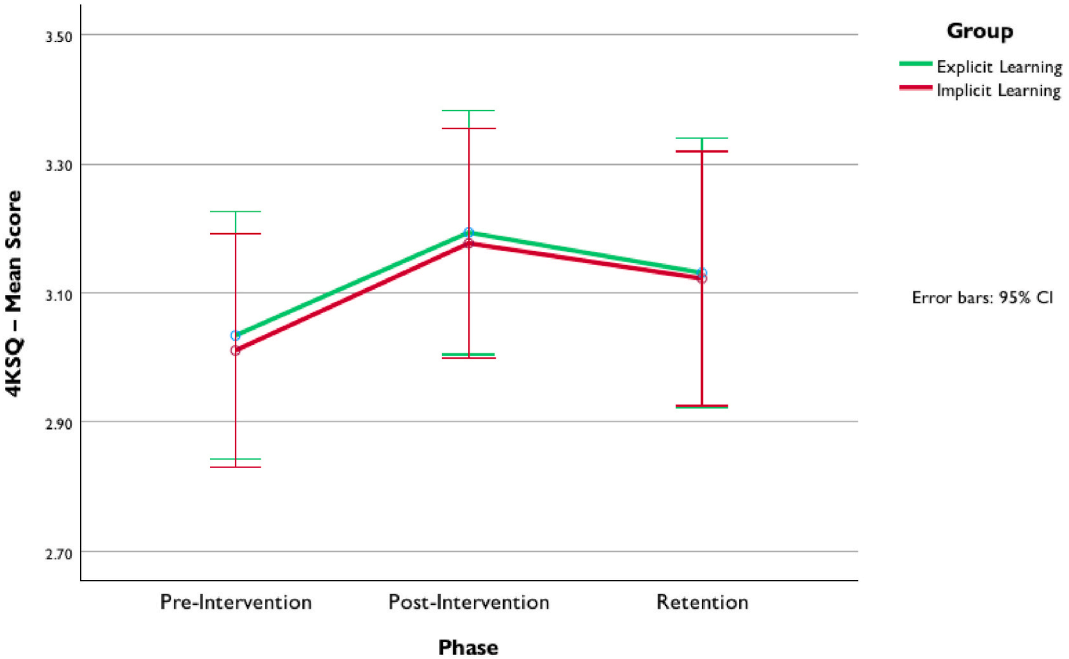

Fig. 8. 4KSQ score, by group and phase – rural location.

Table 2
SATs score – 4KSQ score correlations, by phase and location.

Pearson's *r*		Location	
		Urban	Rural
Phase	Pre-Intervention	$r(44) = 0.38$* $p = .005$	$r(44) = 0.19$ $p = .086$
	Post-Intervention	$r(40) = 0.25$ $p = .063$	$r(40) = 0.20$ $p = .084$
	Retention	$r(44) = 0.28$* $p = .036$	$r(44) = 0.35$* $p = .006$

Note. *p < .05.

36.70, *SD* = 4.29), $p < .001$, 95 % CI = 0.01–4.38, and from Pre-Intervention to Retention (*M* = 36.95, *SD* = 4.54), $p = .040$, 95 % CI = 0.10–5.67.

3.5.2. Rural location

There was no Phase by Group interaction. However, there was a significant multivariate effect of Phase, $F(6,194) = 3.06$, Pillai's Trace = 0.17, $\eta_p^2 = 0.09$, $p = 0.007$.

Univariate tests revealed significant effects of Phase on riders' confidence in their *Control*, $F(1.53,164.07) = 5.13$, $p = .014$, $\eta_p^2 = 0.10$. Bonferroni pairwise comparisons showed that riders' confidence increased from Pre-Intervention (*M* = 32.88, *SD* = 4.41) to Post-Intervention (*M* = 36.02, *SD* = 3.81), $p = .03$, 95 % CI = 1.39–4.83.

3.5.3. Confidence – 4KSQ correlations

Table 3 shows relationships between riders' confidence in their *awareness*, *decisions* and *control*, with their 4KSQ scores, by Phase. All three subcomponents of rider confidence were correlated with 4KSQ scores at Post-Intervention.

3.6. Parental confidence

3.6.1. Urban location

In the multivariate analysis, there was no Phase by Group interaction, $p > .05$. However, there was a main effect of Phase, $F(2,32) = 6.06$, Pillai's Trace = 0.28, $\eta_p^2 = 0.28$, $p = 0.006$.

Univariate tests revealed an effect of Phase on parental confidence in their *child's ability to cycle on roads*, $F(1,33) = 3.16$, $p = .002$, $\eta_p^2 = 0.26$. Bonferroni pairwise comparisons showed that, after viewing their child's POV footage captured during the retention ORCA, at Follow-Up (*M* = 4.49, *SD* = 0.70), their confidence increased from Pre-Intervention (*M* = 4.06, *SD* = 0.87), $p = .002$, 95 % CI = 0.18–0.68.

Over the same period, parental confidence in their own ability to cycle on roads did not change.

3.6.2. Rural location

In the multivariate analysis, there was no Phase by Group interaction, $p > .05$. However, there was a main effect of Phase, $F(2,31) = 9.68$, Pillai's Trace = 0.38, $\eta_p^2 = 0.38$, $p < 0.001$.

Univariate tests revealed an effect of Phase on parental confidence in their *child's ability to cycle on roads*, $F(1,32) = 18.59$, $p < .001$, $\eta_p^2 = 0.37$. Bonferroni pairwise comparisons showed that, after viewing their child's POV footage captured during the retention ORCA, at Follow-Up (*M* = 4.71, *SD* = 0.80), their confidence increased from Pre-Intervention (*M* = 3.91, *SD* = 1.00), $p < .001$, 95 % CI = 0.41–1.14.

Over the same period, parental confidence in their own ability to cycle on roads did not change.

Table 3
Confidence – 4KSQ correlations, by phase.

Pearson's *r*		Phase		
		Pre-Intervention	Post-Intervention	Retention
RiderConfidenceSubcomponent	Awareness	$r(94) = 0.23$* $p = .023$	$r(89) = 0.29$* $p = .006$	$r(88) = 0.20$ $p = .054$
	Decisions	$r(94) = 0.28$* $p = .007$	$r(89) = 0.36$* $p < .001$	$r(88) = 0.19$ $p = .067$
	Control	$r(94) = 0.16$ $p = .135$	$r(89) = 0.27$* $p = .010$	$r(88) = 0.23$* $p = .026$

Note. *$p < .05$.

4. Discussion

We ran two immersive training intervention studies, based in two diverse geographical locations in the United Kingdom, one urban location and one rural location. In the urban location, intervention and control groups were compared, whereas in the rural location two different versions of the immersive intervention were compared – one in which participants heard prerecorded prompts, in the other they did not. Below, we summarise and discuss our findings in the context of the extant literature and our supplementary analyses, highlighting strengths and limitations of the current study design, followed by suggestions for future research directions.

4.1. On-road cycling performance

All urban riders' on-road cycling performance improved across the duration of the study. However, contrary to our expectations, the immersive training and control groups performed similarly, at all phases. Overall, rural riders' performance improved from Pre-Intervention to Post-Intervention only – improvements disappeared at Retention. However, there was no difference in the efficacy of the two different intervention types (Explicit vs. Implicit Learning). The fact that the control group in the urban location performed comparably to the intervention group in the ORCAs, at all phases, suggests that the immersive training had little impact, if any, on the riders' on-road cycling performance, unlike previous findings (Bishop et al., 2022a) – although supplementary data suggest that the prompts led to appropriate observation and communication behaviours during the intervention, albeit there was no relationship between those behaviours and ORCA performance (see SA#1). In fact, it arguably suggests that the key determinant of the improvements observed in all groups, across both locations, could be the independent cycling experience the riders accrued during their completion of each of the ORCAs – in other words, a learning effect – but further research is required to verify this. Importantly, there is good evidence for consistency of the ORCA assessments, across different timepoints, locations, instructors and environmental conditions (see SA#2), suggesting that this could be a useful tool for practitioners when assessing students on-road performance.

4.2. Situation awareness

Riders' performance in the video-based SATs did not markedly improve post-intervention, nor did it differ between groups, at any phase. This is similar to previous research that used video-based tests to assess situation awareness and hazard perception (e.g., Bishop et al., 2022a; Lehtonen et al., 2017; Kovácsová et al., 2020). However, in the current study, SATs scores correlated somewhat positively, albeit weakly, with riders' 4KSQ scores – i.e., their on-road cycling performance. This suggests that the video-based SATs may be a useful screening tool for determining young children's readiness to ride independently on roads or could even supplement on-road training; for example, as part of classroom-based instruction prior to cycling on roads. However, we should note the minor and sporadic nature of these correlations (see Table 3). Also, there were no differences in riders' scores across the three different versions of the SATs (see SA#3) – which suggests that there was equivalence in their difficulty and the situation awareness elements they assessed (perception, comprehension, projection).

Video-based tests are useful for both researchers and practitioners as demonstrating riders' situation awareness on roads is more challenging. In the present study, riders in the on-road assessments were asked to provide a running commentary of their thoughts to try to provide insight into their situation awareness (see transcripts in Supplementary Materials). However, some riders were more loquacious than others, and gusts of wind occasionally masked riders' commentaries. In addition, some rider commentaries were lost due to faulty recordings or failed upload to cloud storage – three from the Intervention group (urban location) and five from the Explicit Learning group (rural location). Nonetheless, we performed a rudimentary analysis of ORCA commentaries (see SA#4), and it suggests that riders' situation awareness did not change markedly over the duration of the study – a finding that is consistent with the SATs data. However, given that these supplementary data were compromised, they should be interpreted with some caution.

4.3. Rider and parent attitudes and confidence

Neither riders' nor parents' attitudes towards cycling changed over the course of the two studies. However, the attitudes of both were positive at the outset – they all tended to agree with positive statements (e.g., *cycling on roads is fun*) and tended to disagree with negative ones (e.g., *cycling on roads is stressful*) (see Supplementary Materials). This may reflect the high levels of cycle ownership and cycling behaviour in this cohort (see Supplementary Materials): they are not representative of the wider UK population, either in terms of cycle ownership, which stood at 47 % of all people in England in 2021; and the 'average person' made 15 cycling trips per year (Department for Transport, 2022).

Confidence in *control* of their movements and cycle increased from Pre-to Post-Intervention for both the urban and the rural riders – an increase that was maintained at Retention in the urban riders only. The urban riders' confidence in their *awareness* also increased from pre-intervention to post-intervention. As for the improvements in ORCA performance, the on-road experiences the riders accrued when completing the ORCAs seems the most viable explanation for increases in riders' confidence in their control, as little control of the cycle was required during the intervention. This is partly supported by our correlational analyses, which show that riders' confidence somewhat correlated with their ORCA performance, albeit mostly at the Post-Intervention phase (see Table 3).

Perhaps more pertinently for active travel behaviour change: parental confidence increased significantly from Pre-Intervention to Follow-Up, after they had viewed their child's POV footage acquired during the Retention phase ORCA, irrespective of group or location – although this was unrelated to their child's 4KSQ score (see SA#5). Parents are strong determinants of their children's cycling behaviour (e.g., Bishop et al., 2024; Wilson et al., 2018; Woldeamanuel, 2016), and so this may be an invaluable intervention all by itself. For example, acquisition of children's POV video footage could be incorporated into Bikeability training, such that parents who do not ride with their children (most UK parents) can see and hear their children's competence and confidence firsthand. This could make them more confident in their child's ability to cycle independently on roads, which could lead to more young riders on UK roads – and 'safety in numbers' (Herslund and Jørgensen, 2003; Tin et al., 2015) could follow, as cyclists become more prevalent road users.

4.4. Study evaluations

The children's evaluations of key elements of the study – the SATs, the intervention and the ORCAs – were highly positive (see SA#6), consistent with recent research in which immersive technology has been employed (e.g., Zeuwts et al., 2023). The SATs were deemed significantly less interesting than the ORCAs, which is perhaps understandable, given their repetitive nature. Additionally, the ORCAs were rated as more useful than the intervention – which adds to our body of evidence to suggest that independent on-road cycling may be more fundamental to rider learning than immersive training.

4.5. Limitations and future research directions

On reflection, while the immersive intervention has many strengths, such as its portability and relative ease to administer by training providers, there were limitations identified with the intervention. Perhaps the most significant was the effect of the reward sounds on the riders' behaviour: In follow-up discussions with the participating instructors, Instructor 4 (rural) commented that *"… the kids … quickly picked up that, 'if I turn my head, I got a bell, and if I got a bell, I got points' … the heads were like owls, and it was just a game, trying to get as many points as they could, and actually not meaningful looks, so that then became a game rather than an intervention"*. This was also an issue for urban riders: *"I found that there were some children that when they found out that there was definitely going to be a bell and they would get a point for it … I had quite a few children … literally just looking and looking and looking and looking over their shoulder to make bells sound so they could get points."* (Instructor 1). So, in hindsight, this element of the intervention was counterproductive to our initial aims, because it encouraged maladaptive head turning behaviour, and possibly reduced participants' attention to the prerecorded prompts. This contrasts with what was arguably more mindful rearward looking in Bishop et al.'s (2022a) study, because participants were required to verbalise the colour of a vehicle over their right should or the presence/absence of a cyclist over their right shoulder; this may be additional evidence for the importance of human-human interaction. Future research is required to scrutinise the gamification of interventions to ensure it encourages riders to adopt correct behaviours and doesn't lead to negative transfer of learned behaviours.

It is important to consider how future immersive cycle training interventions' reach can be maximised; the current one-to-one (e.g., researcher-to-participant) model is neither time- nor cost-effective. A more pragmatic approach to immersive training may be a minimalistic one – i.e., one that requires minimal technological and human resources to deliver it. For example, online training resources (e.g., https://examen.vvn.nl/vvn-theoretisch-verkeersexamen) or and group-based training that can be experienced via devices with built-in gyroscopes, as many contemporary smartphones and tablet devices are. These methods would be comparatively cost-effective and efficient and would consequently have far greater outreach within communities than immersive interventions that require the use of HMDs. That said, the extent of immersion in the video stimuli may also be an important consideration for delivery via devices that do not provide a '360-degree spherical space' as HMDs do. Video resources comprising rider POV footage may be useful and cost-effective learning tools to prepare children for riding on roads, and they need not be in 360-degree video format. That said, more sophisticated situation awareness tests (e.g., ones filmed in 360-degree format and delivered via HMD) could be more appropriate learning and assessment tools than the ones used in this project and may correlate more strongly with ORCA performance as a result. This is also worthy of further exploration.

Another limitation related to the on-road cycling assessments as we did not assess the extent to which the commentaries interfered with the riders' ORCA performances. There is evidence that, with suitable training in such 'think aloud' protocols, there is minimal interference, albeit in competitive cyclists (Whitehead et al., 2022) – but studies in driving suggest that running commentary interferes with hazard perception, even when drivers are given sufficient practice in performing commentaries (Young et al., 2014, 2017). However, the instructions given to participants in the present studies were minimal as this was just supplementary data to support the 4KSQ scores. In future studies, an element of training, and setting clarifying expectations, would undoubtedly improve the quality of on-road cycling assessment commentaries.

Finally, the reasons for the urban Control group's high level of on-road cycling performance throughout the study, including their high rate of improvement, is unexplained. In hindsight, the metrics used to determine riders' cycling experience, and therefore equivalence of groups, could potentially be more comprehensive (cf. Bishop et al., 2022a). Measures relating to the types (e.g., on roads vs. off-road) and quality (e.g., independent vs. in groups) of cycling experiences would be a worthwhile addition to rider characteristics data. For example, in their survey study of 246 children and their parents, Bishop and colleagues (2024) asked questions about the frequency with which respondents performed recreational, commuter and competitive cycling, as well as the frequency with which they cycled short journeys, which enabled the researchers to more clearly define the outcome measure in their path analysis: cycling behaviour. A more detailed level of reporting detail may help to elucidate the effects of immersive training interventions in future studies. In addition, it would be prudent for future research to explore individual differences that might explain such anomalous performance, over-and-above the quality of the participants' prior on-road cycling experiences. For example, using established psychometric measures, future studies could control for cyclists' attentional control (Bishop et al., 2022b), working memory capacity (Broadbent et al., 2023), and risk-taking tendencies (O'Hern et al., 2020), not to mention other individual differences variables.

5. Conclusion

The ability of immersive training interventions to improve children's on-road cycling performance is indeterminate. However, we propose that a combination of independent on-road cycling, immersive training, and video-based situation awareness tests –approximately 2 h of virtual and physical training time – improves children's ability to cycle in accordance with the four key skills of Bikeability training. Collectively, these elements could complement Bikeability training, potentially reducing children's involvement in on-road collisions, increasing their propensity to cycle short journeys, and thereby increasing their physical activity levels and wellbeing accordingly.

CRediT authorship contribution statement

Daniel T. Bishop: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **David P. Broadbent:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Damon Daylamani-Zad:** Supervision, Software, Resources, Methodology, Conceptualization. **Kaisei Fukaya:** Writing – review & editing, Validation, Software, Resources, Project administration, Methodology. **Benjamin R. Smith:** Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: At the time of writing, Dr Bishop and Mr Smith are employees of The Bikeability Trust, with a vested interest in finding evidence to demonstrate the efficacy of cycle training, be it immersive or otherwise. However, because the data were collected independently and remotely by Bikeability instructors, almost exclusively via the JISC online survey platform (the exception being gaze-based reward point data, which were stored locally on the host PCs), and the raw data have been made fully available in the Supplementary Materials, we feel that analysis and reporting have been transparent, and therefore potential biases minimised.

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We also extend our heartfelt thanks to the young riders, their parents, and their schools, for whom the same applies: this study could not have happened without you. Thank you for providing such a large volume of high-quality data; data that will undoubtedly help researchers and practitioners alike to continue to improve our understanding of how we can make cycling a viable option for active travel for future generations.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jth.2025.102048.

Data availability

We have provided the Mendeley Data doi, and we have uploaded additional files with the manuscript.

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