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A brief gamified immersive intervention to improve 11–14-year-olds' cycling-related looking behaviour and situation awareness: A school-based pilot study

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ABSTRACT

Despite the health benefits of active travel, very few people in the UK choose to cycle short journeys; a frequently cited barrier is personal safety concerns. Recent research using immersive video-based training has shown promise, in terms of improving young children's situation awareness and looking behaviour when cycling, although such evidence is sparse. We designed and delivered a brief gamified immersive intervention to address this. Forty-four schoolchildren took part in a 10-minute intervention comprising 360-degree real-world point-of-view footage of a cycle journey through a busy urban environment, experienced via a head-mounted display (HMD) with built-in eye tracking. The participants were split into two groups: an explicit learning group who received instructions regarding adaptive looking behaviour, and an implicit learning group who received no instructions. In a gamified protocol, participants scored points for fixating on target areas that represented adaptive looking behaviour; reward sounds notified them when they were successful. The explicit learning group accrued points more rapidly in the early stages of the intervention, but the implicit learning group matched the explicit group's performance level by the end of the brief intervention. All participants' cycling confidence increased after the brief intervention, and these increases were correlated with their performance in the game, but participants' performance on video-based situation awareness tests did not improve. Brief gamified immersive interventions could be used to develop young cyclists' competence, and therefore confidence, regarding cycling on roads, which could, in turn, encourage them to cycle short journeys.

1. Introduction

Although active travel is associated with a variety of mental and physical health benefits (Jacob et al., 2021), the use of cycling for short journeys in the UK remains a rarity (Department for Transport, 2021). This may be due in part to various barriers, both real and

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perceived, to cycling on roads – the most prominent of which are safety concerns (Chillón et al., 2014; Kirby & Inchley, 2009; Panter et al., 2008). For example, two-thirds of UK adults feel it is too dangerous to cycle on roads (Department for Transport, 2021). These concerns may be well founded: In Great Britain in 2019, only 20 trips per person were made by cycle, <7% of the 295 trips per person made by car or van – but almost 10% of the 36,563 road user casualties reported in that year were cyclists. Distraction and impaired situation awareness are frequently cited causal factors in accidents involving bicycles (Møller et al., 2021; Vanparijs et al., 2016). In the context of cycling, *situation awareness* (Endsley, 1995) is the ability of the cyclist to perceive, comprehend, and anticipate the future status of their immediate environment, including other road users (Bishop et al., 2022). Children are more likely to be serious casualties in accidents involving bicycles (Nicaj et al., 2009), which may reflect the potentially limited impact of road safety education programmes on children's cycling-related looking behaviour and situation awareness (Feenstra et al., 2014; Twisk et al., 2014).

In the UK, Bikeability training requires children to demonstrate their ability to cycle on urban roads in accordance with the UK National Standard for Cycle Training (Department for Transport and Driver & Vehicle Standards Agency, 2019). Specifically, they must demonstrate that they can *make good and frequent observations*, *communicate their intentions clearly to others*, *choose and maintain the most suitable riding positions*, and *understand road user priorities, particularly at junctions* – known as the four *Core Functions*. Moreover, the Bikeability Delivery Guide (The Bikeability Trust, 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" (p. 20). These requirements embody the concept of situation awareness: the cyclist must first perceive elements of their immediate environment, including potential hazards (*perception*), understand how they should respond to those elements (*comprehension*), and then anticipate what they and other road users should, or will, do (*projection*). However, although Bikeability training appears to be effective for developing certain aspects of safe cycling (Hodgson & Worth, 2015), it may not translate into greater propensity to cycle (Goodman et al., 2016). Moreover, adolescents' engagement with training is low (Department for Transport, 2021).

Children's attitudes towards cycling are not only influenced by their own attitudes and self-perceptions (Bjørnarå et al., 2020; Zaragoza et al., 2020), but also those of their parents (Mendoza et al., 2014; Ross & Wilson, 2021). This continues into adolescence (Woldeamanuel, 2016), although it may ultimately be the children's attitudes that determine whether they choose to commute via cycle (Bishop, Natesan Batley et al., 2023; Fitch et al., 2019). There is evidence that school-based interventions targeting children's perceptions and attitudes lead to greater use of cycling as a mode of active travel. In a quasi-experimental study, Villa-González et al. (2017) allocated 494 children aged 8–11 years to an intervention group or a control group. The intervention comprised a variety of activities designed to increase the children's familiarity with active commuting, the urban environment, and road safety. One of the activities was gamified: The children engaged in traditional games which had been adapted for road safety and active commuting educational purposes. At follow-up testing 6 months later, the authors found that rates of cycling to school were greater for boys in the intervention group, whereas rates of passive travel (e.g., car journeys) had increased for girls in the control group. Gamified interventions designed to improve children's attitudes towards cycling may increase their propensity to cycle, especially if based within schools, where peer influences are strong (Corder et al., 2020).

The emergence of virtual reality technology has provided greater opportunity to develop gamified interventions, notably for children, as their engagement with virtual technologies is increasing (Maloney et al., 2021). Virtual environments have been used to assess people's hazard perception in dynamic scenarios including cycling (van Paridon et al., 2019), driving (Sportillo et al., 2018), fire safety (Xu et al., 2014) and emergency medical care (Abulfaraj et al., 2021), and to improve their situation awareness (Endsley, 1995) in traffic (Gounaridou et al., 2021) healthcare (Meijer et al., 2018), and military (DeFalco et al., 2018) contexts, among others. Such interventions are commonly referred to as *serious games* as they combine the development of vital life skills such as risk and hazard perception (e.g., Money et al., 2019) with playful elements that typify many videogames (Djaouti et al., 2011). Moreover, the addition of feedback mechanisms in these interventions, such as rewards, can increase user engagement (Francillette et al., 2021; Paraskevopoulos et al., 2014; Spyridonis & Daylamani-Zad, 2021). However, to our knowledge, a serious game approach to immersive training that incorporates rewards has not yet been used to improve young cyclists' looking behaviour and situation awareness.

Cycling-based studies designed to train or assess young cyclists' situation awareness and hazard perception have normally adopted flat screen-based approaches. For example, Zeuwts et al. (2017) used a video-based hazard perception test comprising cyclist point-of-view (POV) footage presented to young and adult cyclists via a computer monitor. The children were slower to react to hazards, which included being slower to fixate on latent covert hazards – i.e., those that were initially or partially hidden from view. Similarly, using animated video clips, Kovácsová and colleagues (2018) investigated cyclists' eye movements as they navigated a variety of virtual intersections presented on a computer monitor. As traffic complexity increased, the participants scanned their environment more frequently – although their attention was largely directed towards vehicles that posed a more immediate threat to their safety (Frings et al., 2014). These studies collectively suggest that cyclists' looking behaviour may not be conducive to safety on roads, particularly so in children.

Bishop and colleagues (2022) developed an immersive training protocol to improve young children's looking behaviour and situation awareness as they cycled on roads, using a setup in which life-size 360-degree footage was projected onto three flat screens. An intervention group navigated five virtual routes and were required to demonstrate their awareness of potential hazards and other safety-related information (e.g., road signage), by responding to researcher questions throughout the intervention. They also received frequent verbal feedback on the quality of their head turning and eye movements, including rearward looking behaviour. A control group received no training. There were no between-group differences on a video-based situation awareness test, or in self-reported cycling self-efficacy scores, but when assessed by qualified Bikeability cycle instructors on urban roads, the intervention group outperformed the control group in all four Core Functions – and the greatest improvement was in their ability to *make good and frequent observations*. Moreover, these improvements persisted in follow-up retention tests several weeks later. However, while Bishop et al.'s findings are encouraging, the portability of the immersive setup makes it difficult to roll the intervention out on a larger scale. Furthermore, the intervention required continuous feedback from a trained researcher, which restricts the accessibility of the intervention. Improvements in VR technology, such as head mounted displays (HMDs) with built-in head and eye movement tracking, and sophisticated videogame programming software, provide an opportunity to deliver serious game-type interventions with embedded reward mechanisms, that are accessible, affordable, and can be delivered within local communities.

The main aim of the present study was to pilot test whether explicit instructions provided to 11–14-year-olds prior to a cycling-based gamified immersive task delivered via an HMD in a school setting could promote adaptive looking behaviour during the task and improve their performance on video-based situation awareness tests (SATs). A second aim was to assess whether an auditory reward system for appropriate looking behaviour (e.g., towards overt and emerging hazards, and including where they might appear) Our third and final aim was to explore the relationship between the children's performance in the game with changes in their confidence and attitudes, given the importance of these for cycling behaviour change (Bishop, Broadbent et al., 2023; Fitch et al., 2019). Accordingly, we predicted that:

1. A group receiving explicit instructions regarding adaptive looking behaviour would perform superiorly to a group that received no instructions, in both the gamified task and the SATs [H1].
2. A gamified intervention with embedded reward mechanisms for appropriate looking behaviour would lead to increased fixations on high-reward regions in the virtual environment [H2].
3. Changes in confidence and attitudes vis-à-vis cycling on roads would correlate with performance in the gamified intervention [H3].

2. Method

2.1. Participants and study design

Forty-four UK schoolchildren aged 11–14 years ($M = 12.00$ yrs; $SD = 1.00$ yrs; 30 male, 14 female) took part. All participants were children in Key Stage 3 of the UK education system at a high school based in London, UK, and reported that they had normal or corrected-to-normal sight and hearing. Two children suffered from chronic conditions that affected their breathing (asthma and hay fever; these participants were advised to notify the researcher if they wished to cease participation due to breathing difficulties). A range of ethnicities was reported, including White British/Irish (18), Indian (9), Chinese (4), Arab (3), Asian – Other (3), British Indian (2), Black African (1), Black Caribbean (1), Turkish (1) and White Asian (1); one participant did not report their ethnicity. Table 1 shows participants' cycling experience and formal cycle training.

In a mixed design, participants were randomly allocated, with matching for gender and cycling experience, to two groups: an explicit learning group ($n = 22$; 15 M, 7F) that received verbal instructions regarding adaptive looking behaviour as they watched an introductory video and an implicit learning group ($n = 22$; 15 M, 7F) that watched the video but received no instructions. Fig. 1 provides an overview of the experimental protocol.

There were no differences in the two groups' years of cycling without support, $t(42) = 0.41, p = 0.68$, 95% CI = −1.24–1.88, or the frequency with which they cycled, $t(39) = 0.57, p = 0.58$, 95% CI = −1.52–0.86. No outliers or deviations from normality were present in these data. The groups were also comparable in terms of formal cycle training: nine participants in each group had completed Bikeability Level 1 training; seven explicit learning group participants had also completed Level 2 training, compared to six in the implicit learning group; and one participant, in the explicit learning group, had completed Level 3 training. Thirteen participants in each group had received no formal cycle training.

Table 1
Participants' cycling experience and formal cycle training.

Cycling Experience	Group	*M*	*SD*
Years of cycling without support	Explicit	5.77	2.39
	Implicit	5.45	2.72
Frequency of cycling (times per week)	Explicit	2.67	1.91
	Implicit	3.00	1.86
Formal Cycle Training		N	%
Bikeability Level 1	Explicit	9	20.5
(https://www.bikeability.org.uk/get-cycling/cycle-training-for-children/bikeability-level-1/)	Implicit	9	20.5
Bikeability Level 2	Explicit	7	15.9
(https://www.bikeability.org.uk/get-cycling/cycle-training-for-children/bikeability-level-2/)	Implicit	6	13.6
Bikeability Level 3	Explicit	1	2.2
(https://www.bikeability.org.uk/get-cycling/cycle-training-for-children/bikeability-level-3/)	Implicit	0	0.0
None	Explicit	13	29.5
	Implicit	13	29.5

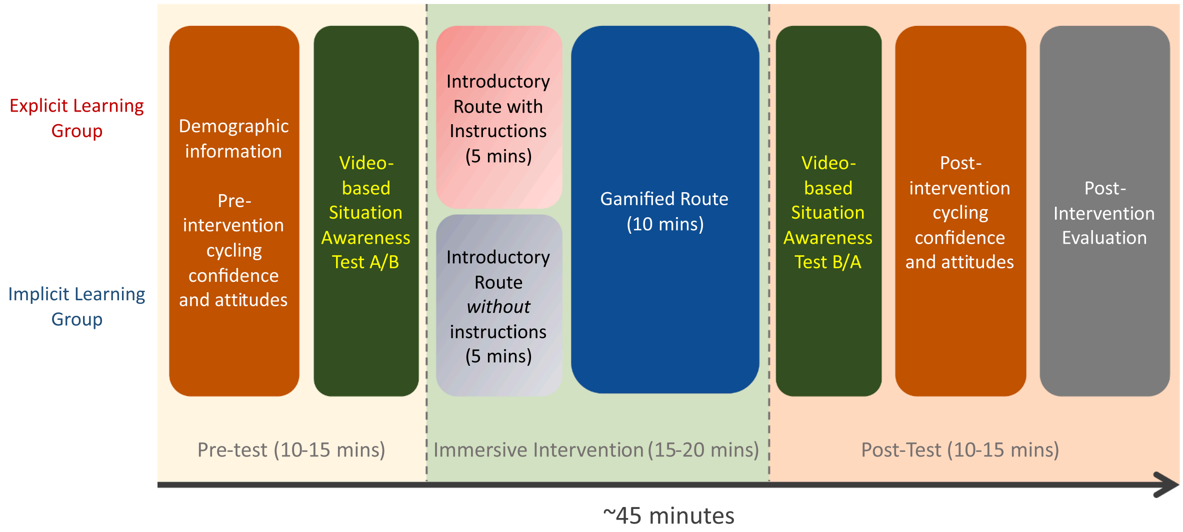

Fig. 1. Overview of the experimental protocol.

2.2. Equipment, materials and measures

2.2.1. Pre- and post-test measures

2.2.1.1. Video-based situation awareness tests. Situation awareness has been investigated extensively in driving (Baumann & Krems, 2007; Endsley, 2020; Underwood et al., 2013) and more recently in cycling (Beanland & Hansen, 2017; Lehtonen, Sahlberg et al., 2017; Lehtonen, Airaksinen et al., 2017). Participants viewed 20 unique video clips, which had been used previously (Bishop et al., 2022), that depicted cyclist POV footage captured on urban roads in the UK between the hours of 0900 and 1700 during British Summer Time, under dry and temperate weather conditions, and comprising varying road user speeds and densities, and a varied representation of junctions including T junctions, crossroads, sideroads and roundabouts. Each video clip was occluded, without a freezeframe followed by a multiple-choice question designed to assess the participants' situation awareness, for example (answer options in *italics*), "What was the car turning in front of you waiting for?" (*Pedestrians* or *A cyclist*), "How many cars were waiting to turn out of the side roads?" (*0* or *1* or *2*), and "Did the car pulling onto the roundabout have its indicators on?" (*Yes* or *No*). Participants provided their responses via the Qualtrics platform. Consistent with the above examples, most of the questions assessed the first level of situation awareness: *perception* (Endsley, 1995). Participants were awarded one point for each correct answer and their total scores were converted into percentages.

2.2.1.2. Cycling confidence and attitudes. Before and after the intervention, participants provided responses via an online survey platform (Qualtrics, Provo, UT) on an 11-point Likert scale *(0 = not at all confident; 10 = extremely confident)*, to the question, "How confident are you in your ability to cycle on the road?", and indicated the extent of their agreement with the following statements, which began with the stem "Cycling…", via a 5-point Likert scale *(1 = Strongly Disagree; 5 = Strongly Agree)*: *is tiring*, *is efficient*, *is stressful*, *is comfortable*, *is convenient*, *is relaxing*, *is enjoyable*, *is good for my physical health*, *is good for my mental health*, and *makes me anxious*.

2.2.1.3. Study evaluation. Participants completed a post-intervention evaluation of the study, in which they responded via Likert scales to rate the *immersiveness*, *usefulness*, *interestingness*, and *realism* of the gamified video intervention. They also provided qualitative data to explain their self-rated likelihood of cycling on roads post-intervention, to indicate their interest in further cycle training, and to answer the following open-ended questions: *What do you think the points were awarded for in the immersive cycle training? What did you like most about the immersive cycle training session? What did you like least about the immersive cycle training session? and What did you learn from the immersive cycle training session? For example, will you do anything differently when cycling on the road?* This was also completed via the Qualtrics platform.

2.2.2. Gamified immersive intervention

2.2.2.1. Video acquisition. 360-degree footage was filmed by the first author using a 360-degree camera (GoPro Max 360-degree; GoPro Inc. CA) which sat atop a bespoke tripod setup mounted on a Hase Trigo cycle (Hase Spezialräder; Waltrop, Germany). The camera was positioned at a height of 60 in. from the ground – approximately the median height of UK 11–14-year-olds – to represent a young cyclist's POV perspective. The footage for both introductory and gamified videos was obtained on major and minor roads in

London, UK, and comprised several junctions including roundabouts, staggered junctions, crossroads, and T junctions. The researcher cycled at an average speed of 10–15 mph, adopted riding positions in accordance with the UK National Standard for cycle training ((DfT & DVSA, 2019) and always observed the UK Highway Code. The footage was imported into GoPro Player (GoPro, 2022) and reframed to always point forwards (POV) for default playback. The reframed footage was then exported as a 4 K (4096 × 2048) MP4 video file for importing into the VR application.

2.2.2.2. Immersive software application. We developed an immersive cycling software application using Unity (https://unity.com) and C#. The application uses Unity's OpenXR Plugin and XR Interaction Toolkit packages, and Tobii XR SDK. It plays back reframed MP4 files for VR as an immersive 360-degree POV video experience whilst tracking the user's gaze. The application allows the user to import 360-degree video; to create and customise fixation target zones, reward sounds, and auditory prompts; and to run the immersive cycle training protocol.

2.2.2.2.1. Gamified Video Intervention – Fixation Target Zones. For the gamified video intervention, elliptical fixation target zones that were invisible to the participant but can be viewed via a computer monitor, were positioned at various points within the spherical VR space relative to cyclist-relevant phenomena in the video footage. Their onsets, durations, sizes, reward values, and associated reward sounds were manipulated accordingly.

Low challenge targets spanned approximately 20 degrees of visual angle with durations ranging approximately 3–5 s. They were typically proximal (approximate real-world distance at target centre: 0.5–10 m) and were located on overt hazards such as overtaking vehicles. Intermediate challenge targets were shorter in duration (range: ~1.5–3.5 s) and comprised emergent and/or covert hazards that were more distal, such as vehicles approaching from side roads (approximate real-world distance: 10–20 m, subtending ~5 degrees of visual angle), and rearward approaching vehicles (approximate real-world distance 5–15 m, subtending ~10–20 degrees of visual angle). Advanced challenge targets were small (~2 degrees of visual angle) distal (approximate real-world distance at target centre: 20–30 m) and fleeting (0.5–2.0 s), necessitating highly anticipatory gaze behaviour, such as early looking towards a location at which another road user might appear (e.g., at the boundary of a fence). The size and location of the targets was manually adjusted during stimuli development, such that their real-world equivalents remained constant.

Fig. 2 illustrates the three types of target. A pedestrian emerging around the near apex of the bend in the road is covered by the small and fleeting target on the left; this is high challenge because fixation on the pedestrian at this point could represent very early detection of that pedestrian. A vehicle emerging from a side road, and the space it is about to occupy, are covered by the slightly larger target; this is more overt than the pedestrian due to its proximity, size, and movement across the visual field. The overtaking car is partially covered by the largest target on the right; this is likely to be fixated reactively, as well as proactively, because the car's proximity, size and movement facilitate attentional capture.

2.2.2.3. Introductory route. All participants navigated a 5-minute introductory route prior to cycling the 10-minute gamified route. During the first minute of each introductory video, participants heard pre-recorded instructions to explain what they would be doing. However, the explicit learning group received additional prompts throughout the remaining four minutes to encourage adaptive

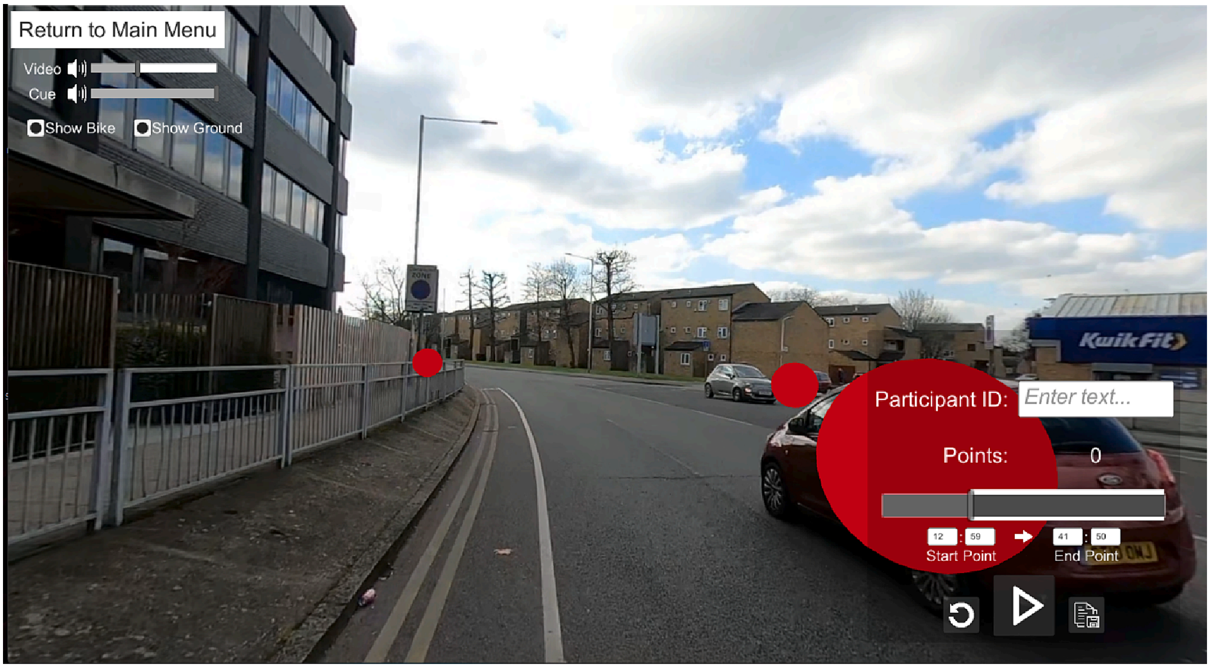

Fig. 2. Examples of advanced, intermediate, and low challenge targets (from left to right).

looking behaviour, for example, *"Did you look down that side road? And did you do it early enough that you would have avoided a collision if a vehicle pulled out?"*. Emphasis was placed on rearward looking, as this vital looking behaviour manifests in superior on-road cycling performance (Bishop et al., 2022); for example, *"Are there vehicles approaching behind you?"*.

2.2.2.4. Intervention setup and protocol. The immersive intervention and pre- and post-intervention measures were completed in the participants' school, in a language laboratory measuring approximately 9 × 3.5 m (see Fig. 3). Participants sat on a 17-inch frame men's all-terrain bicycle, the rear wheel of which was mounted on a cycle trainer; the front wheel was mounted on a riser and the handlebar stem was loosened such that participants could turn the handlebars independently of the wheel and fork. The saddle height was adjusted according to each participant's stature and personal preferences. Crash mats were laid on the floor immediately to the sides of the participant. Participants wore an HTC Vive ProEye (Taoyuan City, Taiwan) HMD throughout the protocol.

2.2.2.4.1. Fixation target reward sounds. Participants' looking behaviour was captured via tracking of their head and eye movements combined (cf. Bishop et al., 2022); customisable audio files – reward sounds – notified them when they had fixated on a target; the threshold for registering a fixation was that the point-of-gaze dwelled on the target for a minimum of 86 ms – the predetermined threshold of the Tobii gaze tracking software. This instant feedback system was designed to promote learning in accordance with the principles of operant conditioning (Dalziel et al., 1989): the participant learns an association between their looking behaviour and the rewards, thereby increasing the likelihood that they will repeat the behaviour (cf. Blaszczynski & Nower, 2002). 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 advanced challenge targets elicited a cash register sound and accrued 10 points. All accrued points were automatically saved for analysis.

2.3. Procedure

Institutional research ethics committee approval was obtained prior to commencing data collection. Children and parents jointly provided their informed consent prior to the child's arrival at the room in which testing took place.

Participants took part during physical education lessons and lunch breaks; they did so individually, in the presence of the researcher only. On entering the room, each participant was invited to sit in front of a desktop PC, whereupon they provided demographic information and reported their cycling-related confidence and attitudes, before completing the first video-based SAT on a PC with a flat screen monitor. The running order of the pre- and post-intervention two SATs (A & B) was counterbalanced across participants and groups. Thereafter, the researcher explained the immersive protocol once more, including explanation that they should pedal and turn the handlebars throughout the immersive routes in accordance with the video footage. The researcher also stated that the participant should immediately notify them if they experienced immersion sickness. After the participant's questions had been answered, the participant mounted the bicycle, with the support of the researcher; saddle height was adjusted as required. Next, the researcher passed the HMD to the participant to put on. Thereafter, the researcher helped the participant to physically adjust the HMD so that its position was optimised and guided the participant through the software calibration process that would enable acquisition of precise gaze fixation data.

Once the participant was comfortable and reported their readiness to commence the protocol, the researcher initiated the introductory video relevant to the participant's group and encouraged the participant to turn the pedals and handlebars in a manner consistent with the video footage. The researcher monitored the participant's performance throughout, both by viewing the computer screen and watching the participant directly. After the introductory video ended, the researcher helped the participant to remove the HMD and take a short break; dismounting was optional.

Fig. 3. The intervention setup.

When ready to recommence with the intervention, the participant reinstated the HMD with support from the researcher, before the researcher recalibrated the gaze tracking software and initiated the gamified intervention video. The researcher provided no feedback regarding the participant's performance during the intervention. After completing the intervention, the participant dismounted the bicycle then completed the second video-based SAT, reported their cycling confidence and attitudes, and provided their evaluation of the study. The researcher subsequently informed them of the points they accrued in the gamified task but did not disclose their performance on the video-based SATs.

2.4. Data analysis

All data were screened for outliers and assessed for normality, homogeneity of variance, and independence of observations, where applicable. For the correlation analyses of self-reported confidence and attitudes towards cycling, we determined the skewness and test–retest reliability of the pre- and post-test measures, in accordance with Steps 1 and 2 of Schumann et al.'s (2022) guidance for handling correlation effects.

2.4.1. Intervention performance

To test our first [H1] and third [H3] hypotheses, two related analyses, which characterised participants' looking behaviour in different ways, were employed.

Firstly, overall points accrued through *target-directed gaze* (i.e., forward and rearward looking combined) was operationalised as the dependent measure for a 3-way (2 *Group* × 3 *Epoch* × 3 *Target*) mixed ANOVA. Three epochs of identical duration (3 min 20 s; one-third of the route duration each) were used to characterise evolution of participants' target-directed looking behaviour over the course of the intervention (*Epoch*; repeated measures factor). A second repeated measures factor, *Target Challenge*, comprising three levels – *Easy*, *Intermediate*, and *Advanced* (see Section 2.2.2.2.1) was included. The between-groups factor was *Intervention Group*: explicit learning or implicit learning.

Given the potential efficacy of promoting rearward looking in child cyclists (Bishop et al., 2022), and the incorporation of related instructions in the explicit learning intervention accordingly, in the second analysis, *forward target points* and *rearward target points* were used as dependent measures to characterise participants' looking behaviour in a 2-way (2 *Group* × 3 *Epoch*) mixed MANOVA,

2.4.2. Video-based SATs

To test our second [H2] and third [H3] hypotheses, pre- to post-test changes in both groups' scores on the video-based SATs were assessed using a 2-way (2 *Group* × 2 *Test*) mixed ANOVA.

2.4.3. Relationship of confidence and attitudes to game performance

To test our fourth [H4] hypothesis, correlational analyses were performed to ascertain the extent of relationships between the percentage of available points participants accrued during the intervention, confidence and attitudes, and their self-reported likelihood of cycling on roads.

Additionally, we used a MANCOVA to explore the potential effect of Group on changes in self-reported cycling confidence and attitudes from pre- to post-intervention, using the total percentage of available points accrued as a covariate; this covariate was included because of our expectations regarding the relationship between participants' game performance and changes in their confidence. Between-group differences in self-reported likelihood of cycling on roads was assessed via an independent samples *t* test.

2.4.4. Study evaluation

The two groups' responses on an 11-point Likert scale ranging from 0 (*Not at all*) to 10 (*Extremely*) to the four questions pertaining to interestingness, usefulness, immersivity, and realism were analysed using a MANCOVA, again using the total percentage of available points accrued as a covariate.

Qualitative data from the participants' responses to the open-ended questions (see Section 2.2.1.3) were organised by Group into tables. Content analysis was performed to aid interpretability where required.

3. Results

3.1. Intervention performance

Visual inspection of the data showed several outliers for percentage of points accrued for forward and rearward looking, across all three epochs. However, most of these reflect the fact that only six participants in the implicit learning group looked rearward in one or more epochs; these individuals had been cycling without support for longer than the sample average and reported an average weekly cycling frequency above the average of the entire sample. Conversely, outliers in the explicit learning group, who had received instructions regarding the rearward looking, were individuals who failed to do so during one or more epochs. Accordingly, Levene's test revealed violations of homogeneity for the percentage of points accrued in rearward looking; there were no other violations of homogeneity in the data. However, we retained all outlying values and made no adjustments for these violations because they did not reflect systematic or random errors, they reflected the experimental manipulation.

Overall Points Accrued, by Group, Epoch and Target Challenge Level. A 3-way mixed (2 [Group] × 3 [Epoch] × 3 [Target Challenge Level]) ANOVA was applied to these data. Mauchly's test revealed a violation of the sphericity assumption for Epoch, Mauchly's $W = 0.83$, $\chi(2) = 7.83$, $p = 0.020$; hence, Greenhouse-Geisser adjustment was applied to the data, $\varepsilon = 0.85$.

Fig. 4 depicts the significant interaction of Group and Epoch, $F(2,84) = 6.01$, $\eta_p^2 = 0.13$, $p = 0.004$. Bonferroni-corrected follow-up comparisons revealed that the explicit learning group ($M = 52.05\%$, $SD = 13.16\%$) accrued more available points than the implicit learning group ($M = 45.43\%$, $SD = 12.57\%$) in Epoch 1, $t(42) = 2.91$, $p = 0.006$, 95% CI = 2.93–16.13, but no differences were found between the groups in Epoch 2 and Epoch 3, which reflects the implicit learning group's increasing accrual of points over the brief intervention.

Fig. 5 shows the significant interaction of Epoch and Target Challenge Level, $F(4,168) = 17.21$, $\eta_p^2 = 0.29$, $p < 0.001$. Bonferroni-corrected follow-up comparisons revealed that participants accrued a greater percentage of advanced challenge target points ($M = 50.49\%$, $SD = 17.66\%$) than Intermediate-level target points ($M = 36.72\%$, $SD = 9.56\%$) in Epoch 2, $t(43) = 5.74$, $p < 0.001$, 95% CI = 8.93–18.60; and a greater percentage of Intermediate-level target points ($M = 44.46\%$, $SD = 10.08\%$) than advanced challenge target points in Epoch 3 ($M = 38.27\%$, $SD = 10.19\%$), $t(43) = 3.26$, $p = 0.002$, 95% CI = 2.36–10.02.

There was a main effect of Target Challenge Level, $F(2,84) = 293.42$, $\eta_p^2 = 0.88$, $p < 0.001$. Bonferroni-corrected pairwise comparisons showed that participants accrued a greater percentage of Easy-level target points ($M = 70.44\%$, $SE = 1.21\%$) than Intermediate-($M = 39.77\%$, $SE = 1.27\%$) or advanced challenge ($M = 41.37\%$, $SE = 1.67\%$) target points, all p's < 0.001 (95% CIs = 27.35–33.99 and 25.16–32.98, respectively).

There was no interaction of Group, Epoch and Target Challenge Level, nor main effects of Group or Epoch, all p's > 0.05.

Points Accrued for Forward and Rearward Targets, by Group and Epoch. A 2-way mixed (2 [Group] × 3 [Epoch]) MANOVA was applied to these data. Mauchly's test revealed no violations of the sphericity assumption, for both dependent variables, p's > 0.05; hence sphericity was assumed. Box's M Test showed unequal covariance of the dependent variables across groups, Box's M = 108.98, $p < 0.001$; hence, Pillai's Trace was reported for multivariate tests.

There was no interaction of Group and Epoch, Pillai's Trace = 0.13, $F(4,39) = 1.50$, $\eta_p^2 = 0.13$, $p > 0.05$.

There was a main effect of Group, Pillai's Trace = 0.50, $F(2,41) = 20.29$, $\eta_p^2 = 0.50$, $p < 0.001$. Follow-up univariate analyses revealed that the explicit learning group accrued a significantly greater percentage of available points from rearward targets than did the implicit learning group, $F(1,42) = 39.74$, $\eta_p^2 = 0.49$, $p < 0.001$, consistent with the explicit instructions they received.

There was also a main effect of Epoch, Pillai's Trace = 0.34, $F(4,39) = 4.93$, $\eta_p^2 = 0.34$, $p = 0.003$. Follow-up univariate analyses showed an effect of Epoch on points accrued from forward targets, $F(2,84) = 5.14$, $\eta_p^2 = 0.11$, $p = 0.008$. Bonferroni-corrected pairwise

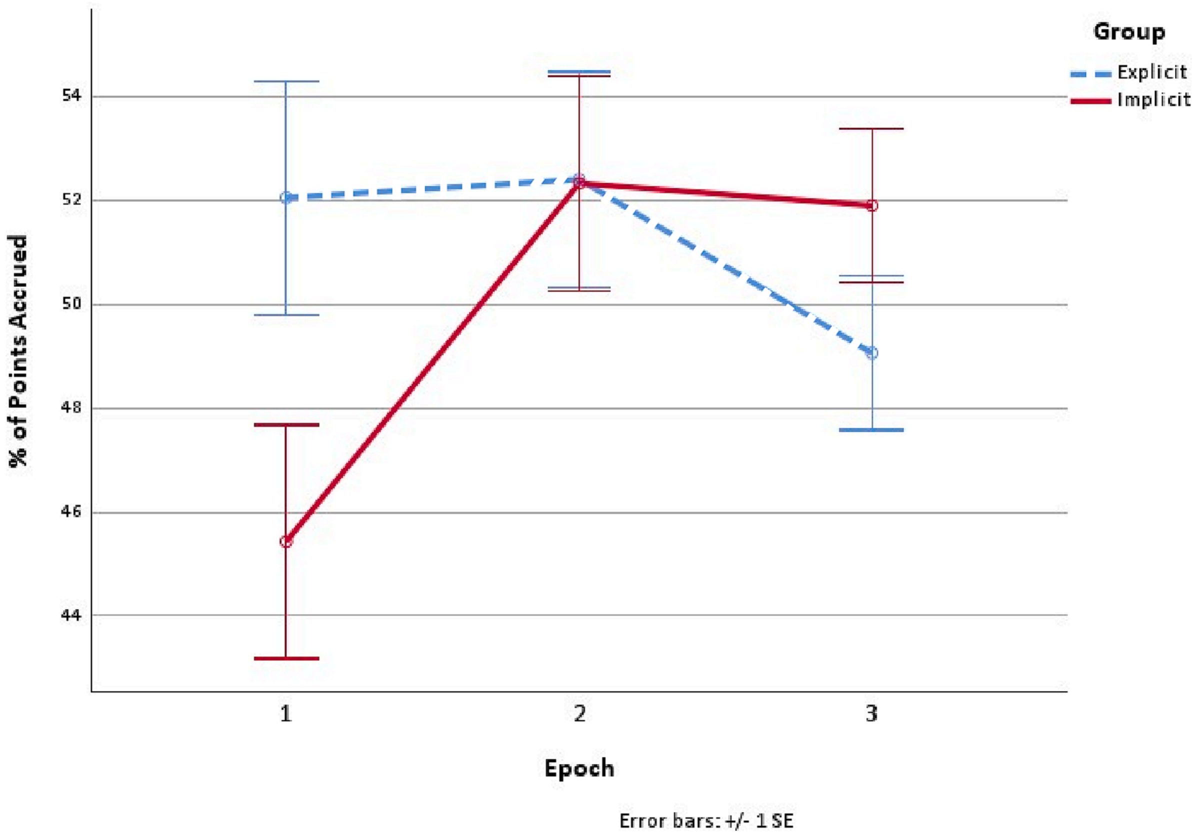

Fig. 4. Group × epoch interaction – effects on percentage of points accrued during the intervention.

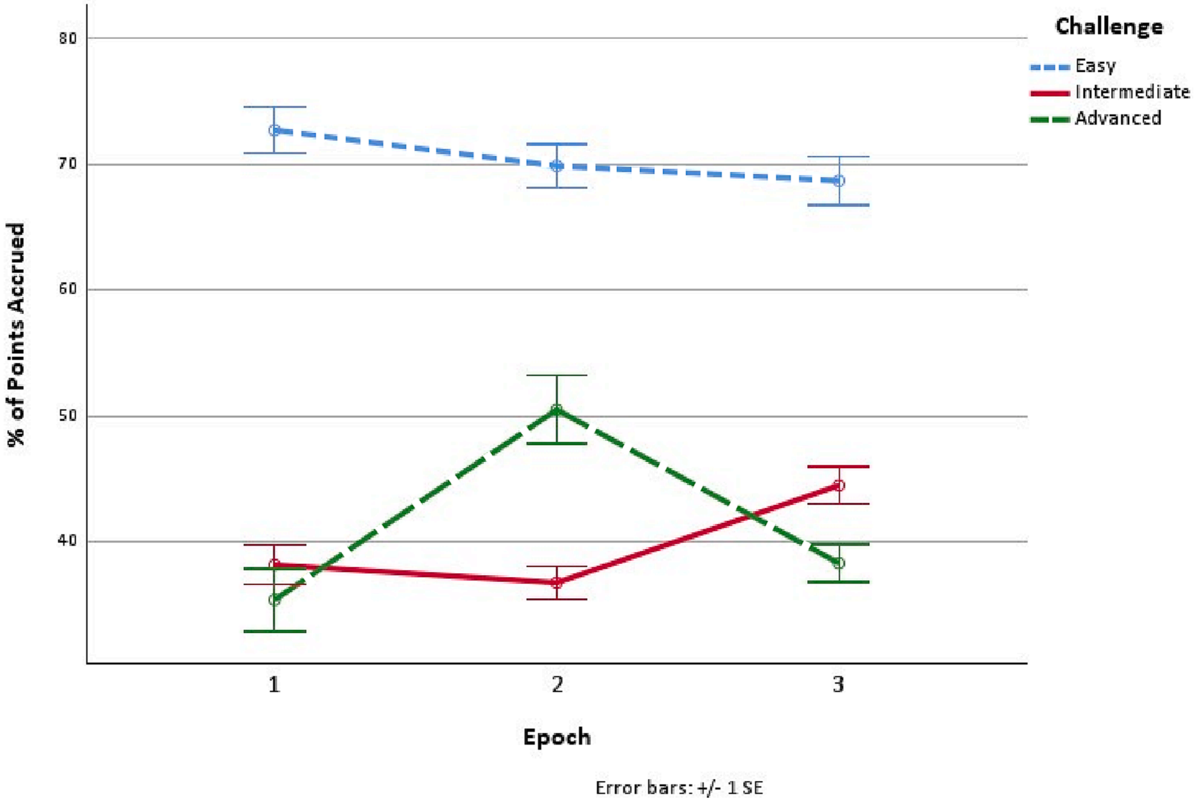

Fig. 5. Epoch-by-target challenge level interaction – effects on percentage of points accrued during the intervention.

comparisons revealed that a greater percentage of available points were accrued from forward targets in Epoch 2 ($M = 51.04\%$, $SD = 11.65\%$) than in both Epoch 1 ($M = 46.68\%$, $SD = 12.86\%$) and Epoch 3 ($M = 46.16\%$, $SD = 8.51\%$).

3.2. Video-based SATs

Levene's Test revealed no violation of homogeneity, $p > 0.05$. There was no significant Group by Test interaction, nor main effects of Group or Test, for SATs scores, all p's > 0.05. Table 2 shows descriptive statistics for participants' SAT scores, by Group.

3.2.1. Relationship of confidence and attitudes to game performance

No outliers or deviations from normality were present in these data (see Table A of Supplemental Material). A correlation matrix showing test–retest correlations between Pre-Test and Post-Test values are shown in Table B of Supplemental Material.

Pre-to-post changes in confidence were positively correlated with participants' percentage of available points accrued, $r(42) = 0.36$, $p = 0.016$, and with their self-reported likelihood of cycling on roads after the intervention, $r(42) = 0.39$, $p = 0.008$.

Pre-to-post changes in perception of cycling as being good for one's mental health were positively correlated with changes in perception of cycling as enjoyable, $r(42) = 0.43$, $p = 0.004$, and as beneficial for one's physical health, $r(42) = 0.55$, $p = 0.001$. The latter was negatively correlated with the perception of cycling as anxiety-inducing, $r(42) = -0.35$, $p = 0.020$. Perceptions of cycling as relaxing and enjoyable were also positively correlated, $r(42) = 0.47$, $p = 0.001$.

There was no effect of Group, nor percentage of points accrued, on participants' confidence and attitudes, $F(11,30) = 0.53$,

Table 2
Participants' SAT scores, by Group.

Group	Phase	Percent Correct			
		M	*SD*	Median	Range
Explicit Learning	Pre-Test	68.45	13.94	69	44–94
	Post-Test	70.18	10.46	69	50–88
Implicit Learning	Pre-Test	69.32	12.97	72	50–88
	Post-Test	71.50	12.49	69	44–94

Hotelling's T = 1.44, and $F(11,30) = 0.64$, Hotelling's T = 1.76, respectively, all p's > 0.05. Moreover, there were no between-group differences in likelihood of cycling on roads post-intervention, $t(42) = 1.37$, $p = 0.179$, 95% CI = −0.43–2.25.

3.2.2. Study evaluation

Table 3 shows participants' responses to a series of post-intervention questions, to which they responded via a Likert scale ranging from 0 (*Not at all*) to 10 (*Extremely*). There were no between-group differences for any items, all p's > 0.05. Qualitative data are in the file *Supplemental Material*.

4. Discussion

We developed a novel and brief gamified immersive intervention to promote adaptive looking behaviour and situation awareness in a group of 44 UK schoolchildren aged 11–14 years, whom we randomly allocated to either an explicit learning or an implicit learning group. All participants completed a 10-minute gamified immersive intervention that comprised 360-degree POV real-world video footage obtained from urban UK roads, after first experiencing a 5-minute route that either comprised instructions designed to promote adaptive looking behaviour (explicit learning group), or a version that comprised no instructions (implicit learning group). We predicted that a group receiving explicit instructions regarding adaptive looking behaviour would perform superiorly to a group that received no instructions, in both the gamified task and the SATs [H1], that a gamified intervention with embedded reward mechanisms for appropriate looking behaviour would lead to increased fixations on high-reward regions of the display [H2], and that changes in participants' confidence and attitudes vis-à-vis cycling on roads would correlate with game performance [H3]. There was mixed support for these hypotheses.

In partial support of H1, there was evidence of changes in participants' looking behaviour according to the instructions we provided in the introductory video, although this did not manifest in superior SATs performance, contrary to H2. The explicit learning group, who received instructions to frequently look rearward, accrued significantly more points from rearward looking than did the implicit learning group. This is consistent with previous findings (Bishop et al., 2022) and demonstrates the potential efficacy of explicit instructions for eliciting changes in children's looking behaviour. The qualitative data supported this finding as there is a preponderance of comments relating to rearward looking in the explicit learning group, whereas there were none from the implicit group (Table G, Supplemental Material). This suggests that the explicit learning group identified at least one rule, as we might expect.

However, performance of the explicit and implicit learning group converged over the brief intervention as the implicit learning group were able to increase their accrual of points in Epochs 2 and 3, suggesting fast adaptation and learning (cf. Madigan & Romano, 2020), such that there were no between-group differences in terms of points accrued during the gamified task. This provides some support for H2, but also contradicts research from the motor learning literature that illustrates differences in golf putting performance between explicit and implicit learners over an extended period of learning (Maxwell et al., 2000). The current findings are possibly testament to the gamified approach we used: In the absence of explicit instructions, implicit learning group participants learned to how to receive rewards, and therefore how to look around adaptively when cycling on roads. Qualitative data supports this assumption as most of the participants indicated that they learned to look around more when cycling (Table G, Supplemental Material) and participants in both groups were equally aware of why they were being awarded points (see Table D, Supplemental Material). Therefore, it appears that many implicit learning group participants also developed at least one explicit rule, which suggests that learning in this group was not entirely implicit in its truest sense (Reber, 2022). There may be implications for training children to cycle regarding the volume of verbal information provided by instructors, but there is a scarcity of research in this regard, so additional investigation is needed.

In further support of H2, we have evidence that all participants' looking behaviour changed over the course of the intervention, such that there were significant increases in points accrued from looking at advanced challenge targets relative to intermediate challenge targets in Epoch 2, albeit that this trend reversed in Epoch 3. The qualitative data in Table G of the Supplemental Material illustrate a greater preponderance in the explicit learning group, of comments relating to anticipatory looking towards advanced challenge targets, such as looking ahead and into side roads in the distance, which also lends some support to H1. That said, there were no significant reductions in the points accrued from easy challenge targets, although visual inspection of Fig. 5 indicates a decreasing trend. A longer intervention period might have yielded significant differences between points accrued for these targets and those accrued for intermediate and advanced challenge targets, but this is clearly speculative and requires closer scrutiny.

The lack of between-groups differences in overall performance on the gamified intervention task could also be explained by a trade-off between forward and rearward looking: When looking behind, it is impossible to accrue points from high challenge targets, which

Table 3
Post-intervention evaluation – average participant ratings (out of 10).

Question	*M*	*SD*
How interesting did you find the first immersive cycling video?	7.82	1.72
How useful did you find the first immersive cycling video for improving your looking behaviour when cycling?	8.34	1.20
How interesting did you find the second immersive cycling video?	8.86	1.29
How useful did you find the second immersive cycling video for improving your looking behaviour when cycling?	8.93	0.97
How immersed were you during the second immersive cycling video?	9.00	1.20
How realistic was the second immersive cycling video?	8.32	1.54
How nauseous did you feel during the second immersive cycling video?	0.91	1.24

were highly anticipatory in nature and consequently located to the front. However, such trade-offs are an accurate reflection of those required in the real world because rearward looking is necessary for successful observation (Bishop et al., 2022) and is one of the four Core Functions of the National Standard for Cycling in the United Kingdom (Department for Transport and Driver & Vehicle Standards Agency, 2019). This notion also warrants closer scrutiny.

Our third hypothesis [H3] was supported: changes in participants' self-reported confidence regarding cycling on roads was correlated with their performance on the gamified intervention task. Moreover, those changes were correlated with their self-reported likelihood of cycling on roads – evidence that their attitudes towards doing so had improved, independently of experimental group. This is consistent with previous research using gamified approaches to improve children's attitudes towards cycling (Villa-González et al., 2017). It may also indicate that associative learning occurred: Participants learned that cycling on roads is a rewarding experience, which predisposed them to feeling more positively about cycling in the real world – perhaps in the anticipation that it would be similarly rewarding, consistent with the tenets of operant conditioning (Blaszczynski & Nower, 2002; Dalziel et al., 1989). This notion is further corroborated by relationships between other attitudinal measures, such as the positive correlation between participants' perceptions of cycling as relaxing and enjoyable; the latter was also positively correlated with the perception that cycling is beneficial for mental health. However, we also wish to acknowledge that the intervening period for our test–retest reliability assessment (see Table B, Supplemental Material) was shorter than is recommended for questionnaire data (e.g., 4 weeks; Schumann et al., 2022).

Realism and immersivity are important features of VR interventions, to increase user engagement (Daylamani Zad et al., 2014; MacRae et al., 2021). Participants' ratings of the interestingness, usefulness, immersiveness, and realism of the intervention video, irrespective of group, were very high – >8 out of 10, on an 11-point Likert scale ranging from 0 (*Not at all*) to 10 (*Extremely*), for all four measures (see Table 2); ratings for the introductory video were similarly high. The data in Tables E and F of the Supplemental Material corroborate these ratings; for example, 16 out of 14 participants responding to the question did not report anything they liked least about the intervention. The feedback and interactivity of our gamified intervention might also have played a crucial role in increasing user engagement (Francillette et al., 2021; Paraskevopoulos et al., 2014; Spyridonis & Daylamani-Zad, 2021). As the prototypical example of an immersive VR serious perceptual training game for cycling, the users' performance and feedback support the positive impact of such interventions, comparable to those previously observed in other domains.

4.1. *Limitations and future directions*

Contrary to our prediction, there were no differences in performance on the SATs, nor improvements in SATs performance over time. A similar lack of between-group differences on this test was reported by Bishop et al. (2022), but the authors noted that their data were collected during the Covid pandemic, which meant that participants completed the SATs in their own homes, albeit doing so face-to-face with the researcher via an online meeting platform. Hence, it was important to assess the viability of these video-based SATs when used under typical controlled testing conditions, i.e., with a researcher physically present. It is possible that these tests lack sensitivity to detect genuine improvements in situation awareness arising from the intervention, because of the nature of the questions: Situation awareness (Endsley, 1995), includes the individual's perception of elements within time and space, their comprehension of the meaning of those elements, and projection of their future state – but the questions in the video-based SATs used in the present study largely assessed participants' perception, at the expense of their understanding and projection. We will investigate this further in future studies, by including questions that require the participants to demonstrate their ability to anticipate road user behaviour (*projection*), as we explicitly trained this skill, and saw evidence that participants improved in their ability to fixate in a more anticipatory manner (i.e., on Advanced challenge targets) as they progressed through the intervention. That said, the gamified immersive intervention task was designed to reward fixation on target regions of the virtual environment, which does not guarantee perception of elements in those regions, let alone comprehension of their significance or projection of their future states. Indeed, the notion of inattentional blindness (Simons & Chabris, 1999), in which we can seemingly look directly at something yet not see it, is well established (Greene et al., 2017; Zivony & Eimer, 2022). Nonetheless, appropriately located point-of-gaze may be vital for maximising detection of movement (D'Innocenzo et al., 2017).

Because of logistical constraints, this pilot study was somewhat underpowered, and so, while the findings provide valuable insight, future research is required to examine the immersive intervention on a larger scale. We also did not have the opportunity to demonstrate positive transfer of learning from our gamified intervention to on-road cycling performance, as was shown previously (Bishop et al., 2022). This is an important next research step, as recent evidence suggests that overconfidence may be associated with riskier behaviour when cycling, including increased violations and a reduction in prosocial behaviours (Bishop, Broadbent et al., 2023). Hence, it would not be prudent to increase young cyclists' confidence for cycling on roads in the absence of demonstrable effects of such interventions on cycling performance. Additionally, we opted not to collect retention test data for the sake of testing brevity and convenience – access to participants was constrained by their study timetables – although this would clearly be prudent in future research efforts that build upon this exploratory study.

Finally, more nuanced data would enable us to better understand the process that underpin the changes in performance, confidence, and attitudes that resulted from the intervention. This applies to data obtained in participants' post-intervention comments and evaluations, eye and head movement data, and SATs performance. In hindsight, although the qualitative responses we obtained are somewhat illuminating, the volume and depth of information we obtained is limited. To better understand changes in children's cycling situation awareness, it would be appropriate to use think-aloud protocols, as these have been used successfully before (Bishop et al., 2022; Ericsson & Moxley, 2011; Money et al., 2019). This will not only provide greater insight regarding the children's thought processes and decision making, but also may act as an educational tool in its own right – particularly so if immediate feedback can be provided regarding the suitably/accuracy of their verbalisations. Such *running commentary* approaches have been used in driver training, albeit with mixed success (Young et al., 2017), and there is scope to use them in assessments of children's situation awareness when cycling. Additionally, acquisition of gaze data would enable us to assess changes in looking behaviour that may underpin self-reports of situation awareness. Similarly, POV video footage to illustrate improvements in children's looking behaviour when cycling, in virtual and/or real-world settings, could be used to increase their parents' confidence in their child's ability to look around appropriately when cycling on roads.

4.2. Conclusion

We developed and pilot tested a brief cycling-based gamified immersive intervention – a *serious game*, which incentivised adaptive looking behaviour in children aged 11–14 years – to see whether it could elicit changes in their looking behaviour, situation awareness, confidence, and attitudes regarding cycling on roads. The evidence suggests this pilot test was moderately effective: The children's looking behaviour evolved over the course of the intervention, it changed according to explicit instructions, but also adapted under implicit learning conditions, and was associated with changes in self-reported cycling confidence and propensity. Gamified immersive interventions may be used as a complement to existing cycle training, to improve children's looking behaviour when cycling, cycling confidence, and propensity to cycle on roads – although further investigative work is needed to substantiate this notion.

CRediT authorship contribution statement

Daniel T. Bishop: Conceptualization, Methodology, Validation, Investigation, Formal analysis, Writing – original draft, Writing – review & editing. **Damon Daylamani-Zad:** Conceptualization, Methodology, Validation, Writing – original draft. **Tamara S. Dkaidek:** Methodology, Validation. **Kaisei Fukaya:** Methodology, Validation. **David P. Broadbent:** Conceptualization, Methodology, Validation, Supervision, Investigation, Formal analysis, Writing – original draft.

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 material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.trf.2023.06.019.

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