Virtual Reality
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The potential of using virtual reality-based self-paced treadmill to assess road-crossing safety and self-evaluation with traumatic brain injuries: a series case study

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Abstract

Impaired self-awareness (ISA) is common following traumatic brain injury (TBI) and can significantly impact safe road-crossing. Road-crossing interventions are variable and involve high-risk real-world situations. Virtual reality (VR)-based road-crossing can elicit changes in real-world functioning but has not been trialled in the TBI population. The primary objective of this research was to explore whether VR-based self-paced treadmill technology offers a safe road-crossing assessment mechanism for people with TBI. Three participants with TBI completed two road-crossing pilot-trials using a VR-based self-paced treadmill. Avatar feedback and verbal feedback were provided between trials. Participants were provided with a safe road-crossing strategy for the second pilot-trial. The Researcher and Participant evaluated road-crossing following each trial using the Mayo-Portland Adaptability Inventory and the number of safe road-crossings to assess changes in self-evaluation and performance between trials. One of the participants perceived improvements in self-evaluation and performance in the second pilot-trial. All participants attempted to apply the safe road-crossing strategy advised. No safety issues were identified using the VR-based self-paced treadmill within this study's protocol thereby supporting the primary objective of the work. Future research is warranted to strengthen the evidence-base for using VR to elicit improvements in ISA in road-crossing and in generalising findings to the wider TBI population.

Keywords Traumatic brain injury · Impaired self-awareness · Virtual reality · Road-crossing · Self-evaluation · Feedback

1 Introduction

Traumatic Brain Injury (TBI) is defined as neuropathological damage and disruption caused by force transmitted to the head (McKee and Daneshvar 2015). TBI causes over 200,000 admissions to hospital annually is the most common cause of death for those under 40 years of age (National Institute for Health and Care Excellence; NICE 2017) and account for almost 50% of all acquired brain injury (ABI) admissions to hospital in the UK (UK; Headway 2017). Care costs for ABI demand £15 billion per annum from the UK economy (Barber et al. 2018).

Dysexecutive deficits following TBI are a common factor impacting return to work and therapeutic outcomes (Weber et al. 2018). Dysexecutive deficits have been shown to occur across all severities of TBI (Barber et al. 2018; Jeffay et al. 2023; McDonald 2002). Impaired self-awareness (ISA) is a common dysexecutive consequence of TBI due to damage to the prefrontal cortex and connecting structures (Doig et al. 2014; Schmidt et al. 2011). ISA has been demonstrated to cause disengagement from therapy, detrimental functional outcomes (Rötenberg-Shpigelman et al. 2014; Schmidt et al. 2011; Schmidt et al. 2013), to hinder realistic goal setting and can elicit overestimation of performance capacity (Al Banna et al. 2016; Schmidt et al. 2011). Failure to accurately estimate performance capacity can lead to task failure which could have catastrophic consequences in a road-crossing context (Butler et al. 2016; Saiano et al. 2015; Schmidt et al. 2011; Toglia and Kirk 2000). Levels of online awareness can be improved through training without an improvement

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in intellectual awareness (Schmidt et al. 2013). This is supported by the Comprehensive Dynamic Interactional Model of awareness (CDIM; Toglia and Kirk 2000). However, measuring ISA continues to present difficulties in research and practice (Lewis and Horn 2013).

Real-world road-crossing assessment is a complex and risk-laden proposition (Butler et al. 2016) necessitating the awareness of and interplay of multiple components for success. These components include mobility, interpretation of traffic speed, awareness of the immediate environment, and anticipation of forthcoming opportunities to cross (Butler et al. 2016). Individuals must monitor and coordinate these components to function safely, which highlights the significant executive demand of road-crossing (Saiano et al. 2015). Increasing people's independence in road-crossing enables them to participate in community occupations and develop their functional independence, for example socialising or shopping (Wright and Wolery 2011), in turn reducing the fiscal impact on society (Butler et al. 2016; Saiano et al. 2015).

The validity and efficacy of current interventions into road-crossing for adults with intellectual deficits are limited by heterogeneity of the groups assessed (Wright and Wolery 2011), indicating that what works for one group may not for another. This evidences the need for exploration of road-crossing strategies with the TBI population; a group neglected in the Wright and Wolery's (2011) systematic review.

Feedback has been shown to elicit positive functional changes in those with ISA (Schmidt et al. 2011; Fitzgerald et al. 2019); however, the protocols used to provide feedback have not been consistently applied impacting on the robustness of this existing evidence (Schmidt et al. 2011). Potential solutions including technology-based interventions such as virtual reality (VR) have demonstrated promise in providing visual feedback in monitoring the movements of participants crossing roads (Saiano et al. 2015; Stratton et al. 2017; Torbaghan et al. 2022). Additionally, the use of concurrent verbal and video feedback can provide a mechanism to reduce the number of performance errors and increase online awareness (Schmidt et al. 2013).

Virtual environments have been shown to elicit changes in real-life performance (Kwon et al. 2022), offering a more time-efficient mechanism for service delivery and reducing the inherent risk in the assessment of road-crossing (Foloppe et al. 2018; Malik et al. 2023; Schwebel et al. 2017). VR scenes have been shown to elicit positive changes in road-crossing errors (Schwebel et al. 2017; Saiano et al. 2015; Stratton et al. 2017), safe road-crossing initiation (Ford et al. 2017) and in reducing road-crossing risk (Clancy et al. 2006) in participant groups which have similar deficits to the TBI population. No research has yet used VR to improve participants' ISA in road-crossing. The avatar reproduction video feedback (AVF) available through VR systems would provide feedback which would be equivalent with the concurrent video and verbal feedback, which has been effective in reducing ISA in previous research (Schmidt et al. 2015).

Self-paced treadmills have been introduced to enhance replication of real-world walking environments when combined with a suitably paced visual flow from a VR projected-screen display. They also enable individuals to reliably adjust and control their own speed of walking (Al-Amri et al. 2017). The use of projected-screen displays alongside self-paced treadmills enables participants to feel included in the environment, but do not over-stimulate, as has been evidenced in the use of head-mounted displays with some participant groups (Schwebel et al. 2017). Al-Amri et al. (2017) demonstrated excellent repeatability in the use of the Gait Real-time Analysis Interactive Lab (GRAIL; Motekforce Link, Amsterdam, the Netherlands) system in gait analysis of healthy individuals when sufficient familiarisation time is provided. Whilst self-paced treadmills have been applied in clinical gait analysis no evidence has yet been identified exploring their potential in assessing road-crossing. Stratton and colleagues (2017) used a manually controlled treadmill to good effect in road-crossing assessment of participants with Multiple Sclerosis without significant adverse effects. No research has yet demonstrated the use of VR-based self-paced treadmills with adult TBI patients.

The use of VR to assess road-crossing and evaluate ISA represents a novel research theory which has the potential to address occupational deficits in the TBI patient group. Therefore, the primary goal of this research was to investigate whether the use of VR-based self-paced treadmill walking is a safe and useable mechanism for assessing road-crossing and self-awareness of performance for people who have experienced TBI. Secondarily, the research investigated whether concurrent AVF and verbal feedback improved road-crossing performance for these TBI participants in a VR setting and whether participants were more able to accurately self-evaluate their performance following feedback.

2 Materials and methods

2.1 Participants

A series case-study methodology was used to support the generation of hypotheses to inform larger studies and future research (Kooistra et al. 2009) regarding the phenomenon of self-awareness of road-crossing performance in people with TBI (DePoy 2016). Five participants with TBI, a suitable number for an investigative series case study (Tellis 1997), were consecutively recruited to support external validity (Kooistra et al. 2009) and purposively sourced through a community brain injury charity (Headway) via advert and letter requests. Prospective participants were still attending

Headway for ongoing input following their TBIs. Those participants expressing a willingness to take part were interviewed to identify whether they had sustained a TBI and how they perceived their road-crossing abilities. Inclusion criteria included: aged between 18 and 64 years old; have sustained TBI and been discharged from hospital; able to ambulate independently in a community setting; and have no visual field deficits following their brain injury. All eligible participants gave written informed consent for inclusion before they participated in the study. Ethical approval was obtained from the School of Healthcare Sciences ethics committee at Cardiff University.

2.2 Procedures

Each participant attended a single assessment visit that took place at the Research Centre for Clinical Kinesiology (RCCK), Cardiff University. The VR system used was the GRAIL system (Fig. 1; MotekForceLink Amsterdam BV) comprising of a self-paced split-belt treadmill with a surrounding 180° semi-cylindrical screen and ten optical infrared cameras to capture movement (Fig. 1; Vicon, Oxford Metrics, Oxford, UK). Twenty-five reflective markers were applied using the Human Body Model lower-body marker set (van den Bogert et al. 2013) on each participant. Kinematic marker data were captured and synchronised at 200 Hz using the motion analysis system to formulate the avatar for AVF. Participants wore tight fitting clothing and suitable shoes for walking on the self-paced treadmill. Participants were provided with a non-weight support harness to reduce the risk of falls and were attached to a suspended rope system via their harness whilst using the treadmill.

2.3 Familiarisation

For familiarisation to the GRAIL system participants completed six minutes walking on the self-paced treadmill using a non-relevant scene and then six minutes using a VR New York Cityscape (Fig. 2; developed by Motek and unlisted by the research team to fit for purpose) projection of a sidewalk interrupted by multiple road-crossings, due to the application used traffic did not cross the paths of the participants when crossing. Verbal instruction was provided to help participants to familiarise themselves with the system.

During familiarisation participants were asked four questions:

(1) Do you feel the VR environment is realistic?
(2) Do you feel safe using the self-paced treadmill?
(3) Do you feel confident adjusting your walking pace on the treadmill?
(4) Are you experiencing any symptoms of cybersickness?

Cybersickness was defined for participants as sensations of dizziness or nausea when using the VR system (Saiano et al. 2015). Participants' responses to these questions were recorded to gain an overview of their experiences using the VR System.

2.4 Pilot-trial 1

Participants completed a 500-m road-crossing program on the VR Cityscape under instruction to cross all roads they encountered. The number of roads they crossed safely (stopping and looking before crossing) was scored through visual assessment by a clinically experienced researcher (an occupational therapist with over 10 years' experience working with patients who have acquired brain injuries, and who

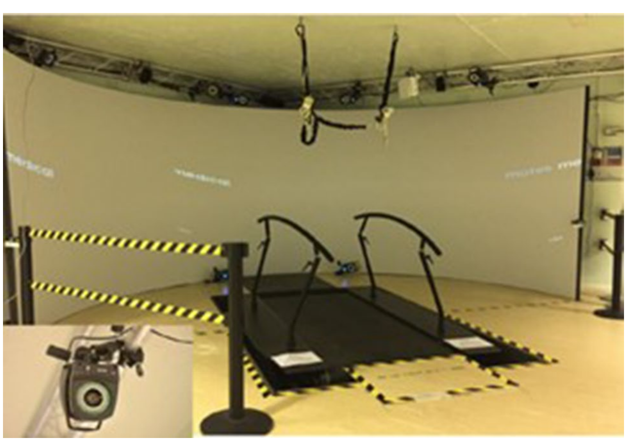

Fig. 1 GRAIL system and Vicon cameras used

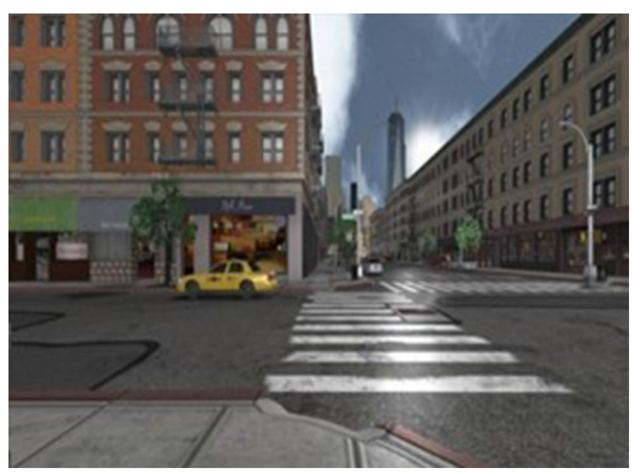

Fig. 2 Cityscape projected-screen display

regularly completes assessments into ISA and road-crossing in a clinical setting). Participants' movements were recorded in the form of an avatar on the GRAIL system.

2.5 Self-assessment following pilot-trial 1

Immediately following assessment, the participants and researcher completed the Mayo-Portland Adaptability Inventory (MPAI-4; Malec and Lezak 2008) to self-evaluate their performance. The MPAI-4 is used to assess ISA in the TBI population (Lewis and Horn 2013) and demonstrates internal consistency (Cronbach's α 0.78–0.88; Malec and Lezac 2008), predictive and concurrent validity with equivalent scales (Malec and Thompson 1994) predictive validity for independent living skills following hospital discharge (r = 0.64; Doig et al. 2014) and sensitivity to clinical changes for both the full measure and its subscales (Guerrette and McKerral 2022; Malec et al 2017). The 29 MPAI-4 items (Table 3) are scored on a 5-point scale (0–4), 0 indicating no limitations and 4 indicating a severe problem interfering with activities more than 75% of the time. Standardised raw scores are attributed to the three Subscales (Activity/Adjustment/Participation) which each have an average score of 50 (SD ± 10). The *T* Score data collected is not comparable to a normative sample but instead provides comparison to others with moderate to severe TBI (Malec and Lezac 2008). *T* Scores of 40–60 are considered typical of those in inpatient or outpatient/community rehab post acquired brain injury. Clarification was provided to participants if they struggled with interpretation of the MPAI-4 instructions. Participants were offered the opportunity to rest and have refreshments.

2.6 Pilot-trial 2

Prior to pilot-trial 2 participants were shown, whilst seated, AVF of their performance using the GRAIL computer to support self-evaluation. Concurrently verbal feedback and recommendations were provided by the researcher. A strategy to "stop, look and cross when appropriate" prior to each road-crossing was provided for application in pilot-trial 2. An appropriate crossing was defined as when there was no impending traffic. The same protocol (as for the first pilot-trial) was then repeated.

2.7 Self-assessment following trial 2

The mechanisms for evaluating their performance were repeated as per pilot-trial 1 including completion of a second MPAI-4. The assessment session in total took approximately one hour including completion of the MPAI-4 with four exposures to VR lasting between six and eight minutes each.

2.8 Data analysis and processing

A mixed approach was applied. Quantitative data were drawn from the researcher and participant MPAI-4 scores and the number of safe road-crossings counted on each trial. Participant comments during the pilot-trials were used to evaluate their perceptions of performance and any experiences of using VR and cybersickness. The number of roads crossed safely across trials was compared for each participant to evaluate changes in road-crossing behaviour. Changes in self-evaluation (MPAI-4) scores were used to assess changes in ISA between trials.

The Reliable Change Index (RCI) was used to indicate any within-participant Change. The Minimal Clinically Important Difference (MCID) and Robust Clinically Important Difference (RCID) measures were also used to indicate clinically important within-participant Change using the MPAI-4. A change of 5 *T* Scores changes between pre- and post-testing indicates MCID, RCID is indicated by a 9 *T* Score difference (Malec et al. 2017).

Participant comments on the equipment, protocol, and experiences of any additional consequences (such as cybersickness) were evaluated following each trial. A subjective self-rating scale of 1/5 (1 indicating absolute failure and 5 indicating absolute perfection) was also used for the participants to evaluate their performance and experience using the VR system.

3 Results

Eleven participants expressed interest in taking part in this research. Five were excluded as they did not meet the inclusion criteria, one withdrew prior to invitation and two participants withdrew from the research prior to data collection resulting in three cases being measured.

3.1 Case histories

Case A Prior to commencing data collection Participant A (35-year-old male, TBI 12 years prior to participation) reported his family have shouted at him to stop as he often does not stop before crossing, that he tends to slow down when road-crossing and has difficulty in judging distance from cars.

Case B Prior to commencing data collection Participant B (55-year-old male; TBI 26 years pre-enrolment) stated he tends to rush into road-crossing not always stopping to look. Participant B felt he tends to take risks in road-crossing since his TBI.

Case C Participant C (40-year-old male; TBI 19 years previously) stated that he had no road-crossing issues since his TBI. Participant C stated that he initially only went out with his wife, but his wife had not expressed any concerns regarding his safety in road-crossing. Participant C reported he had some difficulty reading and required extra time with paperwork. Consequently, he was offered extra time when completing the MPAI-4 and when reading the participant information sheets.

3.2 Familiarisation experience

All participants were able to use the system at the end of familiarisation. Table 1 summarises participants' responses to questions regarding use of the GRAIL system in discussion with the researcher. Participant B struggled to use the self-paced treadmill until the Cityscape projection was introduced. No participants experienced cybersickness, however, participant A was briefly impacted by technical screen-rendering issues (see Table 1).

3.3 Road-crossing pilot-trials

Table 2 presents the performances of each participant during the pilot-trials. All participants were observed to adjust their road-crossing strategy and apply the strategy provided to some extent following AVF and verbal feedback. Participant A did not stop fully before crossing during pilot-trial 2. Participants B and C demonstrated difficulty controlling the speed of the self-paced treadmill during pilot-trial 2. The safety harness and handrails were required to maintain safety in pilot-trial 2. Participants were solely assessed on their application of the safe road-crossing strategy provided during pilot-trial 2.

3.4 MPAI-4 outcomes

Participant and researcher performance evaluation scores were recorded using the MPAI-4 to identify clinically important within-participant difference between trials (Table 3). Participation score changes were unable to be scored (UTS) by the Assessor as the participants were only available for a single day of assessment. This does not impact on the assessment of the Ability and Adjustment Subscales as the MPAI-4 is validated for both the full scale and the subscales (Malec et al. 2017). RCID was observed in both the Ability and Adjustment subscales for participant B, and in their total MPAI-4 score. MCID was observed for participant C in their Participation subscale score between trials. A clinical indication decrease was noted for participant A in pilot-trial 2 compared to pilot-trial 1.

Table 1 Familiarisation experience

Question	Response
Do you feel the VR environment is realistic?	*Participant A* Stated that the VR environment "feels normal" and felt the screen (optic flow) was moving at the right speed
	Participant B Stated he found the VR environment is realistic
	Participant C Felt the screen (optic flow) moved at the appropriate for his walking speed. Participant C feels he needs to look downwards when walking, although he did not feel that this impacted on the VR
Do you feel safe using the self-paced treadmill?	*Participant A* Screen-rendering lag was evident at one point during familiarisation Participant A stated "this feels weird" however was happy to continue
	Participant B Stated he did not feel any anxiety using the treadmill
	Participant C Felt safe using the self-paced treadmill
Do you feel confident adjusting your walking pace on the treadmill?	*Participant A* Stated he felt able to adjust the speed of the treadmill voluntarily
	Participant B Stated that he initially found it difficult to control the self-paced treadmill stating, "it felt a bit weird stopping and judging distance." Multiple explanations were required throughout familiarisation, however this improved using the Cityscape VR environment
	Participant C Felt confident in using the treadmill. He was observed to familiarise quickly with speeding up and slowing down on command. Participant C fluctuated in his speed using the self-paced treadmill
Are you experiencing any symptoms of cybersickness?	*Participant A* Stated that he "Felt a bit dizzy at one point" and reflected that this was due to screen-rendering issues
	Participant B Stated that he did not feel any disorientation, nausea, or dizziness
	Participant C The GRAIL system took "a bit of getting used to," but reported no symptoms of cybersickness

This table provides the responses received by the participants following their use of the VR system during the familiarisation exercise

Table 2 Road-crossing pilot-trials. This table provides the evaluations of participants' road-crossing performances by the researcher (a clinically experienced occupational therapist)

	Pilot-trial 1	Pilot-trial 2
Pedestrian crossing 1	*Participant A* Did not stop walking; however, he looked right and left on approaching the road	*Participant A* Stopped, looked right and left before crossing. Participant A sped up whilst crossing
	Participant B Stopped at the road edge, looked left and right and then crossed	*Participant B* Demonstrated difficulty in controlling the self-paced treadmill needing to use the handrails for support. Participant B was held upright by the harness on stopping, looked for traffic then crossed
	Participant C Stopped early prior to the road edge. He slowly walked to the road edge, looked left and right then crossed at normal walking pace	*Participant C* Stopped abruptly needing to use the handrails to maintain balance; he looked right and left then crossed. Participant C looked right whilst crossing, however his walking pace decreased whilst crossing
Pedestrian crossing 2	*Participant A* Did not stop but looked right and left before crossing	*Participant A* Stopped, looked right and left then crossed. Participant A sped up whilst crossing
	Participant B Stopped well in advance of the road edge. Participant B edged forward on the treadmill and leant forwards to try and look around the corner of the VR street scene. From a standing position participant B then looked left and right and then crossed at his normal walking pace	*Participant B* Stopped at the road edge. Stopped quickly but adjusted. Participant B looked right then left, sped up to cross and continued to look left and right whilst crossing
	Participant C Stopped early prior to the road edge, looked right twice, then stopped again, looked left and then crossed at normal walking pace	*Participant C* Stopped abruptly again and needed to use the handrails to maintain balance, looked right and left at the road edge then crossed. Maintained constant walking pace whilst crossing
Pedestrian crossing 3	*Participant A* Did not stop at the road edge, however looked left then right	*Participant A* Slowed although did not stop before crossing. Looked before crossing, sped up whilst crossing
	Participant B Looked left and right prior to the road edge and did not stop prior to crossing	*Participant B* Stopped, looked left and right and then crossed
	Participant C Variability in pace noted between road 2 and 3. At road 3 participant C Looked left and right prior to reaching the road edge. Participant C slowed as he left the park area of the VR app before the road edge and then crossed the road, he did not stop at the road's edge	*Participant C* Slowed in a more measured manner, looked left and right whilst standing still at the road edge then crossed. Maintained constant pace whilst crossing
Pedestrian crossing 4	*Participant A* Did not stop but looked right and left before crossing	*Participant A* Slowed but did not stop. Looked before crossing. Participant A sped up whilst crossing
	Participant B Looked right then left prior to the road edge and did not stop prior to crossing	*Participant B* Began slowing early and stopped. Participant B looked left and right. On starting he started too quickly and then was pulled back on the treadmill. Demonstrated some difficulty in control of the treadmill
	Participant C Looked right then left prior to the road edge and continued without stopping and crossed at normal walking pace	*Participant C* Stopped abruptly and needed to use the handrails to maintain balance, looked right and left at the road edge then crossed. Between roads 4 and 5 walking pace fluctuated on pavement
Pedestrian crossing 5	*Participant A* Did not stop but looked right and left before crossing. Participant slowed in pace whilst crossing road	*Participant A* Stopped at the edge of the road, looked before crossing. Participant A sped up whilst crossing
	Participant B Looked right then left at the road edge and did not stop prior to crossing	*Participant B* Stopped, looked left and right and then crossed at a good pace
	Participant C Looked right and then left at the road edge, he re-checked for traffic on the left whilst crossing. However, participant C slowed in his pace whilst crossing the road	*Participant C* Looked to the left and right prior to reaching the road, he stopped abruptly and needed to use the handrails to maintain balance. Participant C looked right and left again then crossed. Maintained constant pace whilst crossing

Table 3 This table provides the MPAI-4 Scale scores for each pilot-trial and clinical indications for each participant

	Participant A				Participant B				Participant C			
	Participant		Assessor		Participant		Assessor		Participant		Assessor	
	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2
Ability *T* score	61	58	31	31	47	20**	25	31*	39	41	25	21
Adjustment *T* score	34	30	3	4	46	37**	19	24*	33	29	10	10
Participation *T score*	58	55	UTS	UTS	43	41	UTS	UTS	28	20*	UTS	UTS
Total MPAI-4 T score	62	59	UTS	UTS	47	36**	UTS	UTS	36	35	UTS	UTS
Clinical indication	Severe	Mod-Sev	UTS	UTS	Mild	Mild	UTS	UTS	Mild	Mild	UTS	UTS
Self-score	3	5	4	4	4	5	4	5	4.5	3	4	4

Their self-score rating of their overall performance is included at the foot of Table 3. The use of "UTS" indicates a lack of information available to the researcher due to the single day assessment completed for this road-crossing assessment

UTS = Unable to Score

*MCID; **RCID

Reliable change was calculated to identify any changes in self-evaluation between pilot-trial 1 and pilot-trial 2 using RCI, MCID and RCID (Malec et al. 2017). Using the RCI with a reliable change criterion of 9.19, participant A did not indicate any reliable change between trials. Participant B demonstrated Reliable Change in the activity Subscale (− 27 *T* scores) and in the Total MPAI-4 Standardised Score (− 11 *T* Scores; Table 3). Participant C did not demonstrate RCI between trials for the total MPAI-4 score or in any of the subscales.

3.5 Participant evaluations

Participant evaluations were collected in open questioning during the pilot-trials. A summary of participant responses is included below. Participant A reflected on his "normal" road-crossing behaviour being at odds with the advised safe road-crossing strategy. No participants reported any experiences of cybersickness. Participants B and C reported some difficulty in stopping the self-paced treadmill and Participant C felt that the absence of cars on this road-crossing application meant he did not need to worry when crossing roads. Participant C also reported fatigue and feeling overwhelmed at the end of the session.

4 Discussion

This study used the VR-based self-paced treadmill to assess road-crossing in those with TBI. Our research highlighted no incidents that reduced the participants' willingness to complete the assessment protocol and no participant expressed any safety concerns during assessment or familiarisation (Tables 1 and 4). The familiarisation process enabled all participants to independently use the VR-based self-paced treadmill prior to assessments outside of the pilot-trials (Table 1); this is vital as deficits in information processing and new learning are common consequences of TBI (Pettemeridou et al. 2020).

The experiences of all cases support the contention that VR-based self-paced treadmill road-crossing in TBI groups is safe and usable and further research to support generalisation to the TBI population is warranted. Participant A

Table 4 This table outlines the responses in open-interview following assessment outlining the participants evaluation of using the GRAIL System

Participant	Response
Participant A	Participant A stated, "looking for cars felt strange but in a good way", he reported no cybersickness. He felt that slowing (rather than stopping) at crossings represented his "normal" road-crossing behaviour. He stated that he had "enjoyed doing the assessment and using the VR system"
Participant B	Participant B stated that he experienced no cybersickness symptoms and felt that he had improved technique when using the Cityscape scene, but felt that it was still "hard to judge the stopping" in reference to the self-paced treadmill
Participant C	Participant C felt it was harder to stop using the self-paced treadmill, stating he "stumbled a few times". Participant C felt a "British version" would be preferable. "As there were no cars I didn't worry in the same way". I felt "a little tired at the end and "a little overwhelmed" by the environment

expressed enjoyment when using the VR system and whilst participants B and C demonstrated controlling pace-alteration on the self-paced treadmill during the pilot-trials, the safety harness and handrails ensured that no safety issues occurred (Table 1; Table 4). Participant C reported some cognitive fatigue during pilot-trial 2 which coincided with him having difficulty in completing the MPAI-4 following pilot-trial 2. Increased cognitive and physical fatigue are known consequences of TBI (Headway 2023; Jonasson et al. 2018), which may have contributed to participant C's contrasting scores of self-evaluation and the MPAI-4 ability subscale across trials in comparison to those of the researcher.

All participants attempted to use the safe road-crossing strategy provided in pilot-trial 2 following AVF and verbal feedback between trials. Participant A did not apply the strategy of stopping prior to crossing, however, was observed to slow on each crossing and to check for traffic (Table 2). Both participants B and C were observed to attempt to apply the safe road-crossing strategy in pilot-trial 2 (Table 2). Participant A's improvements may have been impacted in pilot-trial 2 due to well-practiced road-crossing habits which have been in place since his TBI (i.e. not stopping before crossing). This would require a more significant intervention period to elicit performance changes (Schmidt et al. 2011; Weber et al. 2018). Future research is required into using VR practice to reinforce strategies for safe road-crossing and adjust poor technique.

This case-series study demonstrated observational performance changes following verbal and AVF feedback eliciting change in occupational performance (in this case the short-term application of a safe road-crossing strategy), this echoes the findings of Schmidt et al. (2013). This supports the proposition that AVF and verbal feedback can elicit improved road-crossing safety in a VR setting. The results of this case-series highlight the need for further research into using VR and feedback with the TBI population. Further standardisation of road-crossing assessment and intervention in this at-risk population is required (Butler et al. 2016; Wright and Wolery 2011). Improvements in ISA were also identified for participant B who demonstrated RCID between trials (Table 3) and a positive but clinically insignificant change for participant A (Total MPAI-4 change of 3 *T* Scores; Table 3). Further research is required following this series case study to explore the impact of road-crossing practice on ISA in VR with a larger sample size. The researcher scored participant B's performance down in pilot-trial 2 (contributing to this convergence; Table 3), however, discordance between participant and researcher MPAI-4 scoring has been observed previously (Malec and Lezac 2008). Differences in participants' scores can be contributed to by differing values, depression, and impacts of items on participants compared to the researcher (Malec and Lezac 2008). Participant A reported significant limitations due to Anxiety, Depression and Fatigue items on the MPAI-4; these TBI sequelae can affect capacity to self-evaluate (Doig et al. 2014; Schmidt et al. 2011) and may contribute to the scoring disparity observed.

4.1 Limitations

Fatigue was noted on observation of performance in participant C; intensity of assessment should be considered in future research (e.g. reducing the duration of assessment attendances) to reduce cognitive load, thereby preventing overloading which can occur in the TBI population (Stratton et al. 2017). This tallies with participant C's self-reported fatigue following pilot-trial 2 (Table 4).

Regrettably, due to an update of the GRAIL system prior to data collection the electronic avatar and road-crossing scene were played on separate but adjoining computer screens rather than concurrently on one projection. This increased the guidance required from the assessor during the AVF phase of this research. Schmidt et al. (2013) concluded that combined visual and verbal feedback following performance produces the most effective mechanism to elicit change in performance and to increase online awareness; the separation of the avatar recording from the Cityscape scene may have impacted on the efficacy of the intervention applied in this research. However, participants were observed to attempt to apply the strategy provided and thus this does not detract from our conclusion that further research is required into the assessment of road-crossing using VR for those with TBIs.

Utilising self-paced treadmills to stop and then start again may have altered gait patterns and potentially impacted on attention and performance, requiring additional considerations in addition to road-crossing (Al-Amri et al. 2017). These issues were observed for participants B and C during pilot-trials (Table 2). Six minutes has been used previously to familiarise groups to the GRAIL system (Al-Amri et al. 2017); however, information processing, problem-solving and novel learning are dysexecutive consequences of TBI (Pettemeridou et al. 2020) and may have impacted on familiarisation to the GRAIL system for these participants. Previous research has indicated variation in optimal duration of familiarisation across groups (Oude Lansink et al. 2017) and future research will need to consider the 12 min used in this protocol.

The GRAIL system has not been used to assess road-crossing in previous research and further research is required to support its application in this occupation. The use of the GRAIL system to consider behaviours such as direction of gaze and fluidity of movement may benefit future research when assessing road-crossing. Participants without physical deficits impacting their mobility or visual field were considered for this research; however, future research would be beneficial to consider the feasibility of a self-paced treadmill for TBI participants with these deficits.

The dropout rate for this study was greater than 50% and consequently the authors were unable to garner the intended five participants. However, the purpose of this novel research was a preliminary exploration of the use of the GRAIL system in road-crossing with TBI participants who were assessed as single cases.

4.2 Implications for future research

The potential for learning in a VR environment to be applied in a real-world setting has previously been evidenced (Foloppe et al. 2018) as has the potential for VR environments to offer a safe setting to assess risk-laden activities of daily living in a real-world setting (Muratore et al. 2019). VR has the potential to enable domain-specific ISA assessment in a range of occupational settings (Schmidt et al. 2015). Given the safety and usability demonstrated by this research, further research is required developing the generalisability of the findings from this case-series.

Early intervention following TBI elicits the most significant functional outcomes and feedback can bring about positive change in early awareness and orientation deficits (Lucas and Fleming 2005; Teasell and Hussein 2016). Consequently, exploration into early interventions for ISA through VR is vital.

Future research into the use of head-mounted VR systems as opposed to projected-screen displays warrants further investigation. Whilst projected-screen displays have resulted in fewer incidents of cybersickness, accessibility and financial constraints represent barriers to overcome when rolling out this treatment to a larger group. Further research into the comparative benefits of each system would be beneficial to explore the use of VR treatment across the TBI population. A future study considering the comparative worth of real-world road-crossing in comparison to the use of VR would be a logical progression following the positive outcomes of VR road-crossing using the GRAIL system in this study.

5 Conclusions

This series case study is the first to demonstrate the safe use of VR-based self-paced treadmill to assess road-crossing in TBI participants. The use of AVF and verbal feedback with these participants did improve implementation of a safer road-crossing strategy in the short term with all three participants slowing prior to crossing roads in their second pilot-trial on observational assessment. Further research into the use of the self-paced treadmills and particularly the process of familiarisation is warranted.

Clinically important changes were noted for Participant B and positive self-evaluation and performance improvements were observed for Participant A using the MPAI-4, although Participant A's ISA changes were clinically insignificant. Further research is warranted to investigate whether a VR intervention mechanism can elicit positive performance changes in road-crossing and improvements in self-awareness across the TBI population.

The use of the Motek GRAIL VR assessment tool for road-crossing assessment requires further research in the short and long term to explore its usability with TBI participants and its effect on ISA.

This research provides a novel insight into the use of VR to assess road-crossing and ISA with participants who have experienced TBI and supports further examination into whether VR assessment of road-crossing is safe and usable in patients following TBI.

5.1 Key findings

- This series case study is the first to demonstrate the safe use of VR-based self-paced treadmill to assess road-crossing in TBI participants.
- The use of AVF and verbal feedback with these participants did improve implementation of a safer road-crossing strategy in the short term with all three participants on observation by a clinically experienced practitioner.
- This research provides a novel insight into the use of VR to assess road-crossing and ISA with participants who have experienced TBI and further examination across the TBI population is indicated.

5.2 What the study has added

This novel research has explored the application of VR to safely assess road-crossing and ISA in TBI participants. Further research is now required to investigate the generalisability of these findings to the TBI population.

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Declarations

Conflict of interest The authors declare no conflict of interest.

Ethical approval The study was conducted according to the guidelines of the Declaration of Helsinki and approved by the Ethics Committee of The School of Healthcare Sciences at Cardiff University (10 April 2019).

Informed consent Informed consent was obtained from all subjects involved in the study.

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