The effect of a virtual reality environment on gaze behaviour and motor skill learning

David J Harris[1], Gavin Buckingham[1], Mark R Wilson[1], Jack Brookes[2],
Faisal Mushtaq[2,3], Mark Mon-Williams[2,3,4,5], Samuel J Vine[1]

1: School of Sport and Health Sciences, University of Exeter, Exeter, UK, EX1 2LU
D.J.Harris@exeter.ac.uk, G.Buckingham@exeter.ac.uk, Mark.Wilson@exeter.ac.uk,
S.J.Vine@exeter.ac.uk
2: School of Psychology, University of Leeds, Leeds, UK, LS2 9JZ
ed11jb@leeds.ac.uk, F.Mushtaq@leeds.ac.uk, M.Mon-Williams@leeds.ac.uk

3: Centre for Immersive Technologies, University of Leeds, Leeds, UK, LS2 9JZ

4: Bradford Teaching Hospitals NHS Foundation Trust, Bradford, West Yorkshire, UK

5: National Centre for Optics, Vision and Eye Care, University of South-Eastern Norway,
Kongsberg, Hasbergs vei 36, 3616, Norway

Correspondence concerning this article should be addressed to Dr David Harris, School of Sport and Health Sciences, University of Exeter, St Luke's Campus, Exeter, EX1 2LU. Contact: D.J.Harris@exeter.ac.uk. ORCiD: https://orcid.org/0000-0003-3880-3856

Funding – D.H. was supported by a Royal Academy of Engineering UKIC Fellowship. F.M and M.M-W were supported by Fellowships from the Alan Turing Institute and a Research Grant from the EPSRC (EP/R031193/1).

Acknowledgements – The authors would like to thank Marcus Simpson, Emma Haines and Jack Pope for help with data collection.

Conflict of interest – The authors declare no conflicts of interest.

Abstract

Objective. Virtual reality (VR) systems hold significant potential for training skilled behaviours and are currently receiving intense interest in the sporting domain. They offer both practical and pedagogical benefits, but there are concerns about the effect that perceptual deficiencies in VR systems (e.g. reduced haptic information, and stereoscopic display distortions) may have on learning and performance. ‘Specificity of learning’ theories suggest that VR could be ineffective (or even detrimental) if important differences (e.g. perceptual deficiencies) exist between practice and real task performance conditions. Nevertheless, ‘structural learning’ theories suggest VR could be a useful training tool, despite these deficiencies, because a trainee can still learn the underlying structure of the behaviour. We explored these theoretical predictions using golf putting as an exemplar skill.

Method. In Experiment 1 we used a repeated measures design to assess putting accuracy (radial error) and quiet eye duration of expert golfers (n=18) on real putts before and after 40 VR ‘warm up’ putts. In Experiment 2, novice golfers (n=40) were assigned to either VR or real-world putting training. Putting accuracy and quiet eye durations were then assessed on a real-world retention test.

Results. Both visual guidance (quiet eye) and putting accuracy were disrupted temporarily when moving from VR to real putting (Experiment 1). However, real-world and VR practice produced comparable improvements in putting accuracy in novice golfers (Experiment 2).

Conclusion. Overall, the results suggest that: (i) underlying skill structures can be learned in VR and transferred to the real-world; (ii) perceptual deficiencies will place limits on the use of VR. These findings demonstrate the challenges and opportunities for VR as a training tool, and emphasise the need to empirically test the costs and benefits of specific systems before deploying VR training.

Keywords: VR; quiet eye; transfer; stereoscopic; skill acquisition; sport;

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General Introduction

Recent improvements in virtual reality (VR) technology have opened up new avenues for skills training. Particular areas of application include surgery (Frederiksen et al., 2019), rehabilitation (Tieri et al., 2018), and sport (Bird, 2019; Gray, 2019). Investment and technological advancements have led to a step-change in the fidelity of VR environments and, concurrently, this technology has become more affordable and portable. The improved accessibility of VR has opened up new possibilities for training applications, as well as creating a powerful tool to investigate skilled performance (e.g. Craig, 2013; Vignais et al., 2009). Fundamental questions remain, however, about the correspondence between real and virtual environments, and the transfer of skilled performance from the virtual to the real-world (Gray, 2019; Harris, Buckingham, Wilson, & Vine, 2019). Consequently, we aimed to use consumer-grade VR technology to explore: (1) whether a well-learned skill can be disrupted by VR ‘warm-up’; and (2) whether VR can accelerate skill acquisition.

Immersive VR describes a computer-simulated environment supporting real-time interactions with computer generated information via normal sensorimotor processes (Burdea & Coiffet, 2003; Neumann et al., 2018). It is possible to conceptualise VR as a ‘model training method’, in that it allows precise control over the environment, but can be untethered from the normal limitations of the physical world. A simulation can be augmented by varying task constraints (Gray, 2017), or adding feedback information that would be either impractical or impossible during real-world practice (Sigrist et al., 2015).

A number of studies have begun to demonstrate the potential of VR training for the long-term refinement of medical skills such as dental surgery (Al-Saud et al., 2017), and sporting skills such as baseball, juggling, and darts (Düking et al., 2018; Gray, 2017; Lammfromm & Gopher, 2011; Tirp et al., 2015). In addition to the longer-term training of skilled behaviour, VR is also being used to aid mental and physical preparation immediately prior to performance in the real-world (Ross-Stewart, Price, Jackson, & Hawkins, 2018). There is, however, only cursory evidence to support the adoption of VR for either of these purposes. In particular, it remains unknown whether complex sensorimotor skills can be developed effectively using current head-mounted VR display technologies.

Existing evidence from the surgical domain suggests that VR rehearsal of complex motor tasks can be effective. In laparoscopic surgery (a highly dextrous skill), a VR warm up prior to the main surgical procedure appears to have notable performance benefits (Calatayud et al., 2010; Moldovanu et al., 2011; Pike et al., 2017). It is important to emphasise, however, that success in one domain (surgery) does not necessarily equate to success in another (sport), although there may be general principles about effective simulation design that we can identify. Indeed, the differences in the skills required across different sports (and even within a single sport – such as golf) means that each training outcome needs to be tested empirically in order to provide confidence about efficacy. For example, the haptic realism of surgical simulators may explain the findings of these systems being effective warm-up tools for surgeons, but this benefit might not apply to sport if haptic feedback is not present. Additionally, it remains unclear whether the reported benefits within surgical practice are a result of: (i) practicing or priming the motor skill; (ii) increasing focus on the upcoming task; or (iii) refreshing procedural knowledge.

One fundamental concern relating to the use of VR is that the systems can provide unusual perceptual challenges, and the sensory input available to the learner may be different from the real-world performance environment. Current VR technologies often provide limited haptic information (Wijeyaratnam et al., 2019) and conflicting visual depth cues as illusions of 3-dimensional space are created on a 2-dimensional screen (Wann, Rushton & Mon-Williams, 1995; Kramida, 2016). This impoverished input may impair the preparation and execution of motor skills, leading to greater perceptual uncertainty and a more deliberate ‘cognitive’ mode of action control (Bingham, Bradley, Bailey & Vinner, 2001; Harris et al., 2019).

These potentially negative effects may, or may not, be a problem depending on the proposed use of the VR system. For example, the perceptual challenges may only be problematic if the system is to be used as a warm-up device immediately prior to the execution of the skilled behaviour within the real-world. It has previously been demonstrated that VR use can temporarily lead to an impaired ability to focus on a target[1] (Hackney et al., 2018; Mosher et al., 2018), as a result of stress placed on the ocular system and conflicting depth cues in VR. Moreover, just 10 minutes of head-mounted display (HMD) use has been shown to cause transient reductions in oculomotor stability (Mon-Williams et al., 1993; Yamada-Rice et al., 2017). For visually-guided motor skills, such as golf putting, small impairments in oculomotor stability could conceivably have detrimental effects on performance.

It is possible, however, that VR systems that lack suitability as warm-up devices could still be useful for long term skill training. Classical theories of transfer (e.g. identical elements theory; Thorndike, 1906) propose that the successful application of skills from one context to another is contingent on the coincidence of stimulus or response elements between learning and transfer contexts (i.e. specificity), suggesting that sensory differences in VR

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[1] Mosher et al. (2018) and Hackney et al. (2018) found increased tolerance to accommodative and vergence error following HMD use. Accommodation refers to the focusing of the lenses of the eye to maintain a clear image on objects at varying distances, while vergence is the simultaneous horizontal rotation of the eyes to maintain binocular fixations. Accommodation and vergence, while normally closely coupled, are placed in conflict in HMDs as a result of using a fixed screen to present objects at varying depth (Wann, Rushton & Mon-Williams, 1995), which disrupts the normal interdependence of the two depth cues and may subsequently increase tolerance for error.

could prevent generalisation. Nonetheless, some studies have indicated positive transfer of sporting skills learned in a virtual environment (Gray, 2017; Tirp et al., 2015). This is consistent with ‘structural learning’ theories that explain the phenomenon of ‘learning to learn’ (Braun et al., 2010; Raw et al., 2015; White et al., 2014). Structural learning theories suggest that generalisation of motor learning can occur if an individual learns the fundamental dynamics that connect a class of related movements. This can be formalised as the system learning a ‘meta-parameter’ that enables the system to restrict its exploration of state space (and thereby rapidly converge on the parameters necessary to undertake a given task). Thus, learning the structure of a fundamental behaviour (e.g. a golf swing) could allow movements to be scaled across ‘superficial changes’ and subsequently applied to new tasks, as long as invariant features (such as sequencing, relative timing, and relative force) remain constant. It can be seen that ‘structural learning’ theories suggest that skills could be learned in VR and transferred to real-tasks if the VR system allows important invariant features of the behaviour to be trained. Success or failure in this regard will depend heavily on the fidelity of the VR environment (with regard to the critical informational demands of the task) and the specific requirements of the training.

Studies examining visuomotor skills in sport have provided some support for the effectiveness of VR training. For instance, Gray (2017) found positive transfer from VR baseball batting training to real-world performance. The virtual environment used in this study, however, consisted of a large 2D presentation of the approaching baseball and a motion tracked bat, thus avoiding some of the issues arising from the conflicting depth cues that can result from stereoscopic presentation. To understand how visually-guided skills can be learned in VR it is important to investigate the development of abilities beyond simple performance outcomes, such as changes in perceptual-cognitive skills (Gray, 2019). Unfortunately few studies have done so, but a notable exception by Tirp and colleagues

(2015) examined development of the gaze behaviour '*quiet eye'* (QE; Vickers, 1996). The QE period is the final gaze fixation prior to movement execution, the duration of which is proposed to support motor programming in target and aiming tasks, and is an established characteristic of expertise (Lebeau et al., 2016; Vickers, 2007; Walters-Symons et al., 2018). Tirp et al. (2015) found that three sessions practising dart throwing in VR resulted in improvements in throwing accuracy comparable with real-world practice. Additionally, the VR trained group exhibited longest QE durations at post-test, indicating a development of perceptual-cognitive skill.

Commercial HMD systems are the most accessible and versatile version of VR currently available, but may also present the biggest challenges for visually-guided skills (because of stereoscopic presentation issues and limited realistic haptic information). There is great enthusiasm for the use of these systems within many training domains, but often in the absence of a thorough empirical base. We argue that it is important to specify precisely the purpose of the use of the VR system in training (i.e. is it for warm up or fundamental skill acquisition?). We further argue that it is necessary to consider how the VR system might disrupt performance and where it might be effective – and then empirically test whether a specific system achieves the identified goal in the context of a specific skill. In order to illustrate these issues, we examined how golf putting performance, and perceptual-cognitive expertise (in the form of QE) were affected by 'training' within an HMD.

General Methods

Task and Materials

VR golf putting. The VR golf putting simulation was developed using the gaming engine Unity 2018.2.10.f1 and the Unity Experiment Framework (Brookes et al., 2019). The simulation (see Figure 1) was displayed through an HTC Vive HMD (HTC Inc., Taoyuan City, Taiwan), running on a 3xs laptop (Scan Computers, Bolton, UK) with an i7 processer and GeForce GTX 1080 graphics card (NVIDIA Inc., Santa Clara, CA). The Vive is a six degrees of freedom headset which allows a 360-degree environment and 110° field of view. An additional Vive sensor was attached to the head of a real golf club to create the VR putter. The Vive tracker added an additional 89g in weight to the putter (400g). Auditory feedback, mimicking the sound of a club striking a ball, was provided concurrent to the visual contact of the club head with the ball, but there was no additional haptic feedback provided. In the VR environment, participants putted from 10ft (3.05m) to a target the same size and shape (diameter 10.80cm) as a standard golf hole. Participants were instructed to land the ball as close to the target as possible, but the ball did not drop into the hole. The game incorporated ambient environmental noise to simulate a real-world golf course and enhance immersion. The simulation used here has been demonstrated to provide an immersive experience; reveals good construct validity in distinguishing novices from experts; and replicates many of the demands of real putting (see Harris et al., 2019 for more details of the simulation validation).

Real-world golf putting. Real-world putts were taken on an indoor artificial putting green from a distance of 10ft (3.05m) to a target of diameter 10.80cm (regulation hole size). To correspond with the simulation, the hole was filled in, so it remained visible but the ball would not drop in. Participants were not given verbal feedback about the radial errors of puts, but the landing position of the ball was apparent and provided feedback on all trials. All participants used a Cleveland Classic Collection HB 1 putter, and standard size (4.27 cm diameter) white golf balls.

Figure 1. Screenshot of the VR putting simulation (left), the VR putting task (centre) and the participant's view (right).

Eye tracking. During real-world putts, gaze behaviour was assessed using a head mounted eye tracking system (Tobii Pro Glasses 2; Tobii Technology, Sweden), which used dark pupil tracking to record point of gaze at 50Hz. The system has a spatial accuracy of 0.5° in both the horizontal and vertical directions. A circular cursor representing 1° of visual angle indicated the location of gaze in a video image of the scene, which could be viewed in real time on a tablet (Windows Surface Pro) connected via a wireless network. Gaze was calibrated prior to each block of pre and post putts and was recorded for offline analysis.

Putting performance. Putting performance in real-world and VR was assessed using radial error of the ball from the hole, as in Walters-Symons et al. (2018) (i.e. the two-dimensional Euclidean distance between the top of the ball and the edge of the target; in cm). In the real-world condition the distance was measured with a tape measure following each attempt. If the ball landed on top of the hole a score of zero was recorded. On trials where the ball hit the boundary of the putting green (90 cm behind the hole) the largest possible error was recorded (90cm) (as in Moore et al., 2012). Radial error in VR putting was recorded automatically by the simulation.

Quiet eye period. The QE period was operationally defined as the final fixation directed toward the ball, prior to the initiation of the club backswing (Vickers, 2007). A fixation was defined as a gaze maintained on an object within 1° of visual angle for a minimum of 100ms. QE offset occurred when gaze deviated from the ball by more than 1° of visual angle, for longer than 100ms (Moore et al., 2012; Vickers, 2007). The absence of a QE fixation on the ball was scored as a zero, while a missing value was given if there was a lack of QE due to tracking or recording problems. To identify the QE period, we used a method of offline data analysis employed in previous studies (Moore et al., 2012; Walters-Symons et al., 2018). The onset (occurring prior to the critical motor movement; the club backswing) and offset were identified using manual frame-by-frame coding of fixation location from the eye tracking recording.

Experiment 1

VR has been proposed as a preparatory tool or ‘warm up’ in applied environments like sport (Ross-Stewart et al., 2018). If, however, stereoscopic displays cause transient reductions in oculomotor stability (Hackney et al., 2018; Mon-Williams et al., 1993; Mosher et al., 2018) and skills are disrupted by the lack of haptic feedback, VR rehearsal could be detrimental. We explored this issue in Experiment 1.

Methods

Participants

Eighteen expert amateur golfers (11 male, mean age = 29.2 years, SD = 13.7) were recruited from three competitive golf teams (University of Exeter Golf Club, Exeter Golf and Country Club, and Devon Golf men’s first team). All participants had active category one handicaps (≤ 5.0), with an average handicap of 1.7 (SD = 2.5). Participants were provided with details of the study before attending testing, and gave written consent before testing began. Ethical approval was obtained from the University Ethics Committee prior to data collection.

Design

A repeated measures design was used with test (pre, post) as a within-subject variable. Outcome measures were putting accuracy and QE duration.

Procedure

Participants attended the lab on one occasion for approximately 40 minutes. Putting performance and QE duration were assessed pre- and post- rehearsal in the VR golf putting simulator. First, participants performed 40 ‘wash-out’ puts on the real putting green to ensure that, when returning to real-world putting for the post practice assessment, they were not still adapting to the specifics of the green. Next they completed 10 baseline putts on the putting green while wearing eye tracking glasses to record gaze behaviour. Following a 5 minute break, participants then completed the VR rehearsal task, which comprised of 40 putts in VR (two blocks of 20 putts with a short break in between), and immediately returned to the real green for the post practice assessment (a further 10 putts with eye-tracking). Forty rehearsal putts were chosen to allow participants time to become familiar with the VR putting and to allow time for any oculomotor adaptations to occur (as in Hackney et al., 2018; Mosher et al., 2018).

Data analysis

Statistical analysis was performed in JASP (v0.9.2; JASP team, 2018). Data were checked for homogeneity of variance (Levene’s test), skewness and kurtosis. Gaze data for two participants were removed due to poor eye tracking calibration. As the predictions about detrimental effects on the first putts following VR use were relatively exploratory, we adopted a sequential testing procedure and initially tested for differences between average baseline performance and the first putt following VR use. If significant differences were found we intended to test the next putt, and so on, while controlling for type 1 error using a

Bonferroni-Holm correction. Cohen's *d* effect sizes were calculated for all t-tests, and partial eta squared for all F-tests. Additionally, to aid the interpretation of null effects Bayes Factors were calculated using JASP (van Doorn et al., 2019). All data are available through the Open Science Framework (https://osf.io/dchgz/).

Results

Performance. There was no overall difference in real-world putting performance (radial error) between putts at baseline (M=25.5 SD=6.85) and putts following VR practice (M=25.6 SD=6.45), *t*(17)=0.03, *p*=.98, *d*=0.01, BF_{10}=0.24. There was, however, a significant increase in radial error on the first putt following VR practice (M=44.8 SD=22.94) when compared to average baseline putting performance (M=25.5 SD=23.4), *t*(17)=3.54, *p*=.003, *d*=0.84, BF_{10}=16.96 (see Figure 2). As this test was significant, we additionally tested the second putt. There was no significant difference between the second putt (M=24.83 SD=16.36) and average baseline performance *t*(17)=0.16, *p*=1.00, *d*=.04, BF_{10}=0.25, so no further tests were performed.

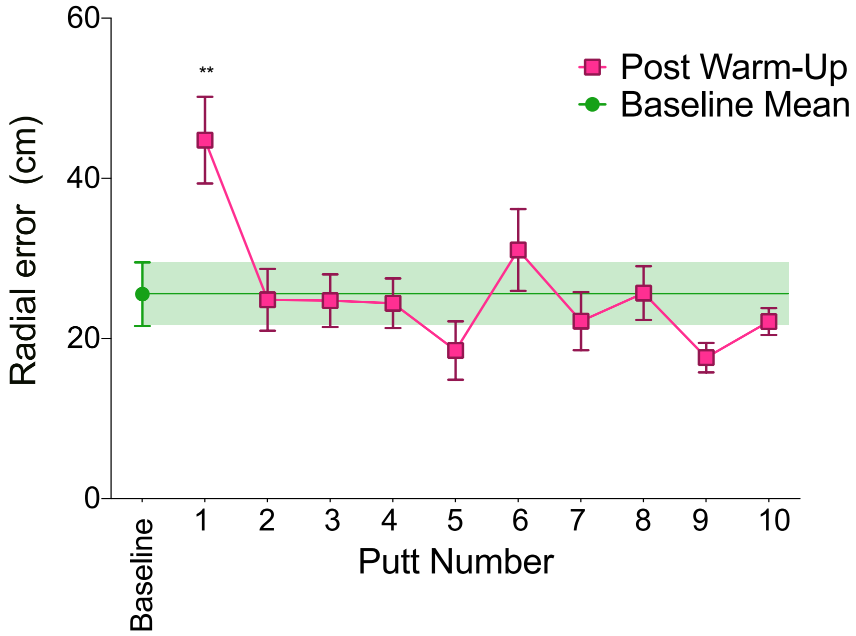

Figure 2. Putting radial error (mean and standard error) at baseline and across the 10 putts following the VR warm up. **significantly different from baseline.

QE period. There was no overall difference in QE duration between putts at baseline (M=1516.8 SD=634.8) and putts following VR practice (M=1380.1 SD=593.7), $t(15)=1.14$, $p=.27$, $d=0.29$, $BF_{10}=0.45$. There was, however, a significant reduction in QE on the first putt following VR practice (M=1073.9 SD=803.7) when compared to average baseline putts (M=1516.8 SD=634.8), $t(15)=2.81$, $p=.01$, $d=0.70$, $BF_{10}=4.34$ (see Figure 3). As this test was significant, we also tested the second putt, while correcting for multiple comparisons. There was no significant difference between baseline QE and the second post-test putt (M=1324.46 SD=790.07), $t(12)=1.58$, $p=.28$, $d=.44$, $BF_{10}=0.76$, so no additional tests were run.

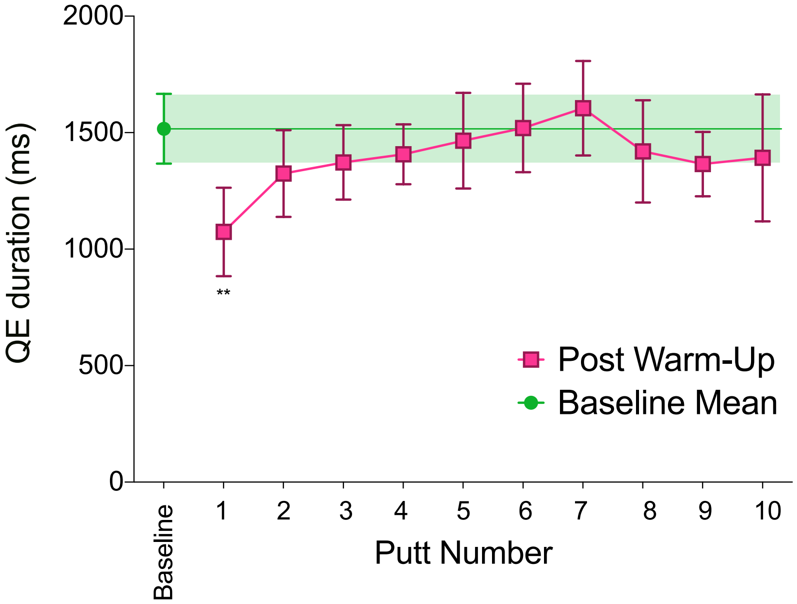

Figure 3. QE durations (mean and standard error) at baseline and across the 10 putts following the VR warm up. **significantly different from baseline.

Discussion

The possibility of using VR for preparation immediately prior to sporting competition is appealing, but the unusual visual and haptic elements of VR may disrupt performance (Harris et al., 2019; Mosher et al., 2018; Wann, Rushton, & Mon-Williams, 1995; Wijeyaratnam et al., 2019). Experiment 1 explored potential disruptions to gaze behaviour and putting performance following VR rehearsal. It was predicted that VR rehearsal could have a detrimental effect in expert golfers with finely tuned putting skills, owing to the subtle visual and haptic differences between the real and virtual skill. In line with this prediction, there was an impairment in performance on the first putt immediately following VR rehearsal (d=0.84). It is known that oculomotor stability and the ability to focus on a target can be impaired following HMD use (Hackney et al., 2018; Mon-Williams et al., 1993; Mosher et al., 2018). We therefore predicted that there would be a transient impairment to QE following the VR warm-up. Indeed, there was a disruption to QE on the first putt of the post-test block, which was over 500ms shorter than baseline putts (a large effect, d=0.73).

The results from Experiment 1 suggest that athletes should be wary of using VR as a warm-up or preparatory tool for finely tuned visuomotor skills. For other purposes, such as mental preparation (Ross-Stewart et al., 2018), VR may well be effective but unless the visual and haptic elements of the real task can be simulated very closely, VR rehearsal could disrupt motor skills.

Experiment 2

Predicated on the rationale that VR could be a useful tool for helping one learn the underlying structure of a task, as suggested by structural learning theories (Braun et al., 2010), Experiment 2 aimed to examine whether training in VR could transfer to real-world performance improvements in novice golfers.

Participants

Forty novice golfers (21 female, mean age=21.6 years, SD=1.5) were recruited via convenience sampling from the University of Exeter undergraduate population. Qualification as a novice was based on having no official golf handicaps or prior formal golf putting experience (as in Moore, Vine, Cooke, Ring, & Wilson, 2012). Participants were provided with details of the study before attending testing, and gave written consent before testing began. Ethical approval was obtained from the University Ethics Committee prior to data collection.

Design

In line previous work in this area (e.g. Lammfromm & Gopher, 2011) we adopted normal physical practice of the skill as the relevant causal contrast (Karlsson & Bergmark, 2015), in order to compare changes resulting from VR practice with real putting. A mixed design was used, with training (real-world, VR) as a between-subject factor and test (pre, post) as a within-subject variable. Outcome measures were putting accuracy (radial error in cm) and QE duration (in milliseconds).

Procedure

Participants visited the lab on two occasions, lasting approximately 30 minutes and 15 minutes respectively. On the first visit, participants completed three practice putts and 10 baseline putts in both the real-world and VR conditions, in a counterbalanced order. Both real and VR putts were from 10ft, as in Experiment 1. Participants were instructed to land the ball as close to the ‘hole’ as possible. Participants were given no instructions about quiet eye or how to execute the putts. Participants were then randomised to either VR or real-world training, and completed an additional 40 putts, divided into four equal blocks separated by a one minute break. This is a similar volume of practice to other short duration golf putting training studies, (e.g. Shafizadeh, McMorri, & Sproule, 2011). Participants returned two days later for post-tests where they completed an additional 10 putts in both VR and real-world conditions (in a counterbalanced order, with a 5 minute break).

Data Analysis

Statistical analysis was performed in JASP (v0.9.2; JASP team, 2018). Data were checked for homogeneity of variance (Levene's test), and skewness and kurtosis. Performance data (individual putts) exceeding three standard deviations from the mean were excluded. Gaze data for nine participants (one in the VR group and eight in the RW group) were removed due to poor tracking. A 2 (Training group: real-world vs VR) x 2 (Test: pre vs post) mixed ANOVA was run on radial error scores (VR and real-world) and QE durations to compare the two groups pre and post training. Cohen's *d* effect sizes were calculated for all t-tests, and partial eta squared for all F-tests. Additionally, to aid the interpretation of null effects, Bayes Factors were calculated using JASP (van Doorn et al., 2019). All data are available through the Open Science Framework (https://osf.io/dchgz/).

Results

Performance. To examine the effect of training on putting accuracy in the real-world, a 2 (group) x 2 (test) mixed ANOVA was run on radial error scores (Figure 4). Overall there was a significant improvement in putting accuracy after training, (i.e. a main effect of test: $F(1,38)=9.90, p=.003, \eta_p^2=.21$, $BF_{10}=11.92$), but no difference between groups, $F(1,38)=0.30, p=.59, \eta_p^2=.01$, $BF_{10}=0.43$ and no interaction, $F(1,38)=0.01, p=.92, \eta_p^2=.00$, $BF_{10}=0.30$.

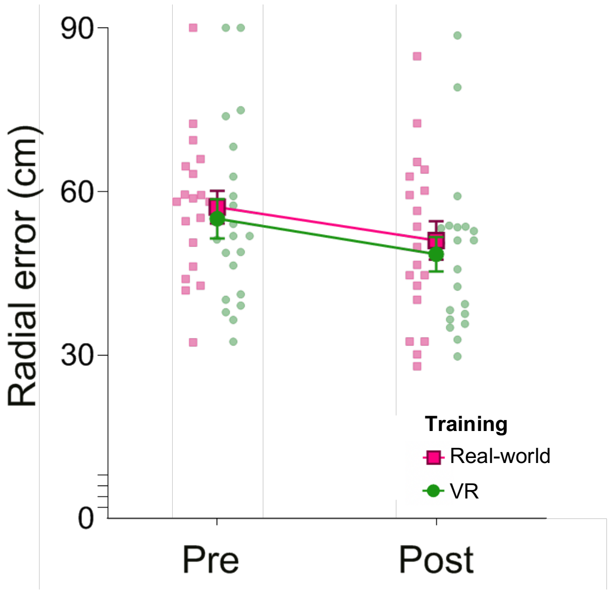

Figure 4. Radial error scores of VR and real-world trained groups on the real-world putting task. Individual data points are shown overlaid on group-mean scores, with error bars indicating standard error of the mean.

To examine the effect of training on putting accuracy in the VR simulation, a 2 (group) x 2 (test) mixed ANOVA was run on radial error scores (Figure 5). There was no overall improvement in putting accuracy, *F*(1,38)=0.02, *p*=.89, η_p^2=.00, BF$_{10}$=.23 and no overall difference between groups, *F*(1,38)=1.11, *p*=.30, η_p^2=.03, BF$_{10}$=.42. As there was a significant interaction effect, *F*(1,38)=5.32, *p*=.03, η_p^2=.12, BF$_{10}$=3.35, Bonferroni-Holm corrected t-tests were run to examine the change in performance of each training group. There was no change in performance in the real-world training group *t*(18)=1.16, *p*=.261, *d*=.27, BF$_{10}$=0.43, but a significant improvement in accuracy was observed in the VR trained group, *t*(20)=2.77, *p*=.024, *d*=.61, BF$_{10}$=4.40.

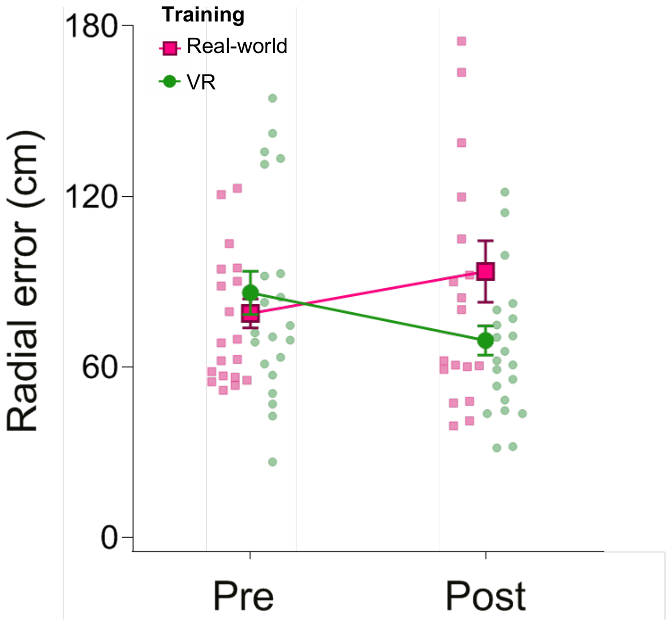

Figure 5. Radial error scores of VR and real-world trained groups in the virtual putting environment. Individual data points are shown overlaid on group-mean scores, with error bars indicating standard error of the mean

QE duration. To examine the effect of training on gaze behaviour, a 2 (group) x 2 (test) mixed ANOVA was run on QE durations (Figure 6). There was a no change in QE post training, F(1,28)=0.16, p=.69, η_p^2=.01, BF_{10}=0.27, no difference between groups, F(1,28)=0.24, p=.63, η_p^2=.01, BF_{10}=0.40, and no interaction, F(1,28)=0.10, p=.75, η_p^2=.00, BF_{10}=0.36.

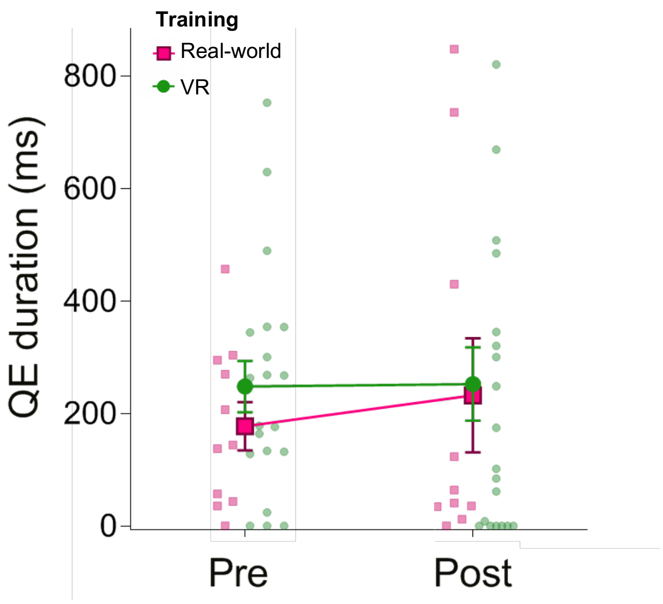

Figure 6. Mean QE durations of VR and real-world trained groups during the real-world putting task. Error bars represent standard error

Discussion

We aimed to examine whether invariant features of the skill of putting could be trained using VR, enabling skill transfer. In line with our primary hypothesis, both real-world and VR putting training induced large improvements in real putting accuracy at post-test. A similar level of improvement was seen between real-world (10.7%) and VR (11.9%) trained groups, indicating that VR training was as effective as the causal comparator, real-world training.

In contrast to our prediction that both groups would also improve their VR putting performance, only the VR-trained group showed improved accuracy in the simulator. The real-world trained group showed a non-significant decrement in performance (*d*=.27; see Figure 5). The transfer of skills from VR to the real-world but not in the opposite direction is consistent with the well-established phenomenon of 'dual adaptation' where adaption to a sensory arrangement is more rapid after repeated experience (Welch, Bridgeman, Williams et al. 1998). Dual adaptation predicts that participants would adapt faster to the addition of haptic information (as this is the predominant experience) than its removal.

General discussion

While VR holds much promise for training, there is currently a limited understanding of how VR might be best implemented to augment performance. In Experiment 1, we show that VR rehearsal can have a potentially detrimental effect in expert golfers with finely tuned putting skills, possibly owing to the subtle visual and haptic differences between the real and virtual skill. In Experiment 2, we show that the same VR environment can be a powerful tool for helping novice learners acquire an understanding of the fundamental structure of a task, and demonstrate that this learning can positively transfer to real-world performance. Together, these results point to a nuanced interpretation on the value of VR-based training for skill acquisition, and we discuss the implications of these results.

Despite the disruptive effects observed in Experiment 1, the benefits of VR training in Experiment 2 support the predictions of structural learning theories (Braun et al., 2010) and suggest that VR can be an effective tool for visuomotor skill learning, if used in the right way. Structural learning accounts explain the transfer of motor skills to new tasks, and suggest that learning a related skill (i.e. the VR version in this case) can reduce the dimensionality of the movement space that must be searched when moving to a new task. Even though there were differences between the real and VR putting tasks, practise of the putting skill in VR may have allowed the extraction of invariants that helped the subsequent performance of the real skill. Consequently, effective uses of VR may well include learning simple invariant features (e.g. limb coordination for the golf swing) during early stages of learning, but are unlikely to include refinement of already well-learned skills.

Thanks to rapid advancements in immersive technologies, it is now possible to create computer-generated training environments with high fidelity and face validity at increasingly low price points. However, far from being a panacea for skill acquisition, there are potentials risks and pitfalls that come from poor implementation of 'training' that will provide little benefit (and indeed, may prove detrimental to learning). There is a requirement to test the costs and benefits of specific systems and consider the skills being trained if we are to take advantage of these technological advances to train athletes. Consider, for example, the impact of the subtle disparity in weight between the real and VR tracked putters (400g vs 490g) in our experiments. This difference (owing to the addition of a sensor on the putter head) altered the putter's moment of inertia. The impact of this difference on novices appears to be negligible, but for our experienced golfers, putting accuracy was disrupted (albeit transiently).

It should also be borne in mind that the positive training effects observed in Experiment 2 occurred for participants at a very early stage of learning. It is reasonable to expect that the benefits of greater specificity in real-world training (Proteau, 1992) might become evident over an extended training period. As studies to date have largely employed similarly brief training interventions, we suggest future work should examine extended training durations. It should also be noted that while we observed performance improvement as a result of VR training in Experiment 2 there was no accompanying improvement in perceptual skill, which may take more time to develop. Finally, to further our understanding of whether skills learned in VR are fundamentally the same as those learned in the real-world, the impact of concurrent tasks and performance pressure should be explored.

Conclusion

VR approaches have huge potential to provide novel training solutions for sports skill acquisition. However, there needs to be a careful examination of the costs and benefits of specific systems and a consideration of the skills being trained prior to the implementation of these technologies in an athlete's training regime.

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