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

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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

1   Recent improvements in virtual reality (VR) technology have opened up new avenues

2 for skills training. Particular areas of application include surgery (Frederiksen et al., 2019),

3 rehabilitation (Tieri et al., 2018), and sport (Bird, 2019; Gray, 2019). Investment and

4 technological advancements have led to a step-change in the fidelity of VR environments

5 and, concurrently, this technology has become more affordable and portable. The improved

6 accessibility of VR has opened up new possibilities for training applications, as well as

7 creating a powerful tool to investigate skilled performance (e.g. Craig, 2013; Vignais et al.,

8 2009). Fundamental questions remain, however, about the correspondence between real and

9 virtual environments, and the transfer of skilled performance from the virtual to the real-

10 world (Gray, 2019; Harris, Buckingham, Wilson, & Vine, 2019). Consequently, we aimed to

11 use consumer-grade VR technology to explore: (1) whether a well-learned skill can be

12 disrupted by VR 'warm-up'; and (2) whether VR can accelerate skill acquisition.

13   Immersive VR describes a computer-simulated environment supporting real-time

14 interactions with computer generated information via normal sensorimotor processes (Burdea

15 & Coiffet, 2003; Neumann et al., 2018). It is possible to conceptualise VR as a 'model

16 training method', in that it allows precise control over the environment, but can be untethered

17 from the normal limitations of the physical world. A simulation can be augmented by varying

18 task constraints (Gray, 2017), or adding feedback information that would be either

19 impractical or impossible during real-world practice (Sigrist et al., 2015).

20   A number of studies have begun to demonstrate the potential of VR training for the

21 long-term refinement of medical skills such as dental surgery (Al-Saud et al., 2017), and

22   sporting skills such as baseball, juggling, and darts (Düking et al., 2018; Gray, 2017;

23   Lammfromm & Gopher, 2011; Tirp et al., 2015). In addition to the longer-term training of

24   skilled behaviour, VR is also being used to aid mental and physical preparation immediately

25   prior to performance in the real-world (Ross-Stewart, Price, Jackson, & Hawkins, 2018).

26   There is, however, only cursory evidence to support the adoption of VR for either of these

27   purposes. In particular, it remains unknown whether complex sensorimotor skills can be

28   developed effectively using current head-mounted VR display technologies.

29   Existing evidence from the surgical domain suggests that VR rehearsal of complex

30   motor tasks can be effective. In laparoscopic surgery (a highly dextrous skill), a VR warm up

31   prior to the main surgical procedure appears to have notable performance benefits (Calatayud

32   et al., 2010; Moldovanu et al., 2011; Pike et al., 2017). It is important to emphasise, however,

33   that success in one domain (surgery) does not necessarily equate to success in another (sport),

34   although there may be general principles about effective simulation design that we can

35   identify. Indeed, the differences in the skills required across different sports (and even within

36   a single sport – such as golf) means that each training outcome needs to be tested empirically

37   in order to provide confidence about efficacy. For example, the haptic realism of surgical

38   simulators may explain the findings of these systems being effective warm-up tools for

39   surgeons, but this benefit might not apply to sport if haptic feedback is not present.

40   Additionally, it remains unclear whether the reported benefits within surgical practice are a

41   result of: (i) practicing or priming the motor skill; (ii) increasing focus on the upcoming task;

42   or (iii) refreshing procedural knowledge.

43   One fundamental concern relating to the use of VR is that the systems can provide

44   unusual perceptual challenges, and the sensory input available to the learner may be different

45   from the real-world performance environment. Current VR technologies often provide

46   limited haptic information (Wijeyaratnam et al., 2019) and conflicting visual depth cues as

47   illusions of 3-dimensional space are created on a 2-dimensional screen (Wann, Rushton &

48   Mon-Williams, 1995; Kramida, 2016). This impoverished input may impair the preparation

49   and execution of motor skills, leading to greater perceptual uncertainty and a more deliberate

50   'cognitive' mode of action control (Bingham, Bradley, Bailey & Vinner, 2001; Harris et al.,

51   2019).

52   These potentially negative effects may, or may not, be a problem depending on the

53   proposed use of the VR system. For example, the perceptual challenges may only be

54   problematic if the system is to be used as a warm-up device immediately prior to the

55   execution of the skilled behaviour within the real-world. It has previously been demonstrated

56   that VR use can temporarily lead to an impaired ability to focus on a target[1] (Hackney et al.,

57   2018; Mosher et al., 2018), as a result of stress placed on the ocular system and conflicting

58   depth cues in VR. Moreover, just 10 minutes of head-mounted display (HMD) use has been

59   shown to cause transient reductions in oculomotor stability (Mon-Williams et al., 1993;

60   Yamada-Rice et al., 2017). For visually-guided motor skills, such as golf putting, small

61   impairments in oculomotor stability could conceivably have detrimental effects on

62   performance.

63   It is possible, however, that VR systems that lack suitability as warm-up devices

64   could still be useful for long term skill training. Classical theories of transfer (e.g. identical

65   elements theory; Thorndike, 1906) propose that the successful application of skills from one

66   context to another is contingent on the coincidence of stimulus or response elements between

67   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.

68   could prevent generalisation. Nonetheless, some studies have indicated positive transfer of

69   sporting skills learned in a virtual environment (Gray, 2017; Tirp et al., 2015). This is

70   consistent with 'structural learning' theories that explain the phenomenon of 'learning to

71   learn' (Braun et al., 2010; Raw et al., 2015; White et al., 2014). Structural learning theories

72   suggest that generalisation of motor learning can occur if an individual learns the

73   fundamental dynamics that connect a class of related movements. This can be formalised as

74   the system learning a 'meta-parameter' that enables the system to restrict its exploration of

75   state space (and thereby rapidly converge on the parameters necessary to undertake a given

76   task). Thus, learning the structure of a fundamental behaviour (e.g. a golf swing) could allow

77   movements to be scaled across 'superficial changes' and subsequently applied to new tasks,

78   as long as invariant features (such as sequencing, relative timing, and relative force) remain

79   constant. It can be seen that 'structural learning' theories suggest that skills could be learned

80   in VR and transferred to real-tasks if the VR system allows important invariant features of the

81   behaviour to be trained. Success or failure in this regard will depend heavily on the fidelity of

82   the VR environment (with regard to the critical informational demands of the task) and the

83   specific requirements of the training.

84   Studies examining visuomotor skills in sport have provided some support for the

85   effectiveness of VR training. For instance, Gray (2017) found positive transfer from VR

86   baseball batting training to real-world performance. The virtual environment used in this

87   study, however, consisted of a large 2D presentation of the approaching baseball and a

88   motion tracked bat, thus avoiding some of the issues arising from the conflicting depth cues

89   that can result from stereoscopic presentation. To understand how visually-guided skills can

90   be learned in VR it is important to investigate the development of abilities beyond simple

91   performance outcomes, such as changes in perceptual-cognitive skills (Gray, 2019).

92   Unfortunately few studies have done so, but a notable exception by Tirp and colleagues

93   (2015) examined development of the gaze behaviour '*quiet eye*' (QE; Vickers, 1996). The

94   QE period is the final gaze fixation prior to movement execution, the duration of which is

95   proposed to support motor programming in target and aiming tasks, and is an established

96   characteristic of expertise (Lebeau et al., 2016; Vickers, 2007; Walters-Symons et al., 2018).

97   Tirp et al. (2015) found that three sessions practising dart throwing in VR resulted in

98   improvements in throwing accuracy comparable with real-world practice. Additionally, the

99   VR trained group exhibited longest QE durations at post-test, indicating a development of

100   perceptual-cognitive skill.

101   Commercial HMD systems are the most accessible and versatile version of VR

102   currently available, but may also present the biggest challenges for visually-guided skills

103   (because of stereoscopic presentation issues and limited realistic haptic information). There is

104   great enthusiasm for the use of these systems within many training domains, but often in the

105   absence of a thorough empirical base. We argue that it is important to specify precisely the

106   purpose of the use of the VR system in training (i.e. is it for warm up or fundamental skill

107   acquisition?). We further argue that it is necessary to consider how the VR system might

108   disrupt performance and where it might be effective – and then empirically test whether a

109   specific system achieves the identified goal in the context of a specific skill. In order to

110   illustrate these issues, we examined how golf putting performance, and perceptual-cognitive

111   expertise (in the form of QE) were affected by 'training' within an HMD.

112   **General Methods**

113

114   **Task and Materials**

115   **VR golf putting.** The VR golf putting simulation was developed using the gaming

116   engine Unity 2018.2.10.f1 and the Unity Experiment Framework (Brookes et al., 2019). The

117   simulation (see Figure 1) was displayed through an HTC Vive HMD (HTC Inc., Taoyuan City,

118   Taiwan), running on a 3xs laptop (Scan Computers, Bolton, UK) with an i7 processer and

119   GeForce GTX 1080 graphics card (NVIDIA Inc., Santa Clara, CA). The Vive is a six degrees

120   of freedom headset which allows a 360-degree environment and 110º field of view. An

121   additional Vive sensor was attached to the head of a real golf club to create the VR putter. The

122   Vive tracker added an additional 89g in weight to the putter (400g). Auditory feedback,

123   mimicking the sound of a club striking a ball, was provided concurrent to the visual contact of

124   the club head with the ball, but there was no additional haptic feedback provided. In the VR

125   environment, participants putted from 10ft (3.05m) to a target the same size and shape

126   (diameter 10.80cm) as a standard golf hole. Participants were instructed to land the ball as close

127   to the target as possible, but the ball did not drop into the hole. The game incorporated ambient

128   environmental noise to simulate a real-world golf course and enhance immersion. The

129   simulation used here has been demonstrated to provide an immersive experience; reveals good

130   construct validity in distinguishing novices from experts; and replicates many of the demands

131   of real putting (see Harris et al., 2019 for more details of the simulation validation).

132   **Real-world golf putting**. Real-world putts were taken on an indoor artificial putting

133   green from a distance of 10ft (3.05m) to a target of diameter 10.80cm (regulation hole size).

134   To correspond with the simulation, the hole was filled in, so it remained visible but the ball

135   would not drop in. Participants were not given verbal feedback about the radial errors of puts,

136   but the landing position of the ball was apparent and provided feedback on all trials. All

137   participants used a Cleveland Classic Collection HB 1 putter, and standard size (4.27 cm

138   diameter) white golf balls.

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

160 fixation was defined as a gaze maintained on an object within 1° of visual angle for a

161 minimum of 100ms. QE offset occurred when gaze deviated from the ball by more than 1° of

162 visual angle, for longer than 100ms (Moore et al., 2012; Vickers, 2007). The absence of a QE

163 fixation on the ball was scored as a zero, while a missing value was given if there was a lack

164 of QE due to tracking or recording problems. To identify the QE period, we used a method of

165 offline data analysis employed in previous studies (Moore et al., 2012; Walters-Symons et al.,

166 2018). The onset (occurring prior to the critical motor movement; the club backswing) and

167 offset were identified using manual frame-by-frame coding of fixation location from the eye

168 tracking recording.

Experiment 1

170 VR has been proposed as a preparatory tool or 'warm up' in applied environments

171 like sport (Ross-Stewart et al., 2018). If, however, stereoscopic displays cause transient

172 reductions in oculomotor stability (Hackney et al., 2018; Mon-Williams et al., 1993; Mosher

173 et al., 2018) and skills are disrupted by the lack of haptic feedback, VR rehearsal could be

174 detrimental. We explored this issue in Experiment 1.

Methods

Participants

177 Eighteen expert amateur golfers (11 male, mean age = 29.2 years, SD = 13.7) were

178 recruited from three competitive golf teams (University of Exeter Golf Club, Exeter Golf and

179 Country Club, and Devon Golf men's first team). All participants had active category one

180 handicaps (≤ 5.0), with an average handicap of 1.7 (SD = 2.5). Participants were provided

181 with details of the study before attending testing, and gave written consent before testing

182 began. Ethical approval was obtained from the University Ethics Committee prior to data

183 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

208   Bonferroni-Holm correction. Cohen's *d* effect sizes were calculated for all t-tests, and partial

209   eta squared for all F-tests. Additionally, to aid the interpretation of null effects Bayes Factors

210   were calculated using JASP (van Doorn et al., 2019). All data are available through the Open

211   Science Framework (https://osf.io/dchgz/).

212   **Results**

213   **Performance**. There was no overall difference in real-world putting performance

214   (radial error) between putts at baseline (M=25.5 SD=6.85) and putts following VR practice

215   (M=25.6 SD=6.45), $t(17)=0.03$, $p=.98$, $d=0.01$, $BF_{10}=0.24$. There was, however, a significant

216   increase in radial error on the first putt following VR practice (M=44.8 SD=22.94) when

217   compared to average baseline putting performance (M=25.5 SD=23.4), $t(17)=3.54$, $p=.003$,

218    $d=0.84$, $BF_{10}=16.96$ (see Figure 2). As this test was significant, we additionally tested the

219   second putt. There was no significant difference between the second putt (M=24.83

220   SD=16.36) and average baseline performance $t(17)=0.16$, $p=1.00$, $d=.04$, $BF_{10}=0.25$, so no

221   further tests were performed.
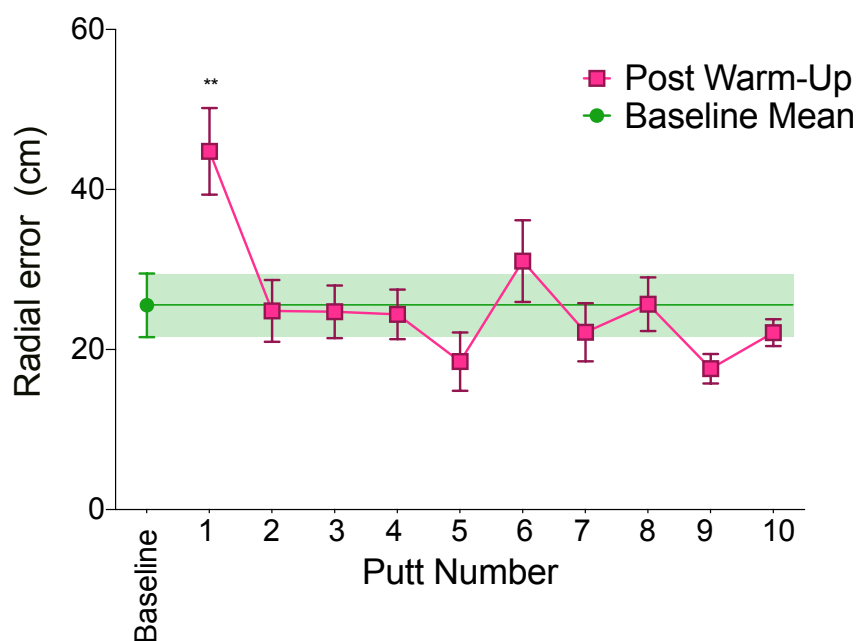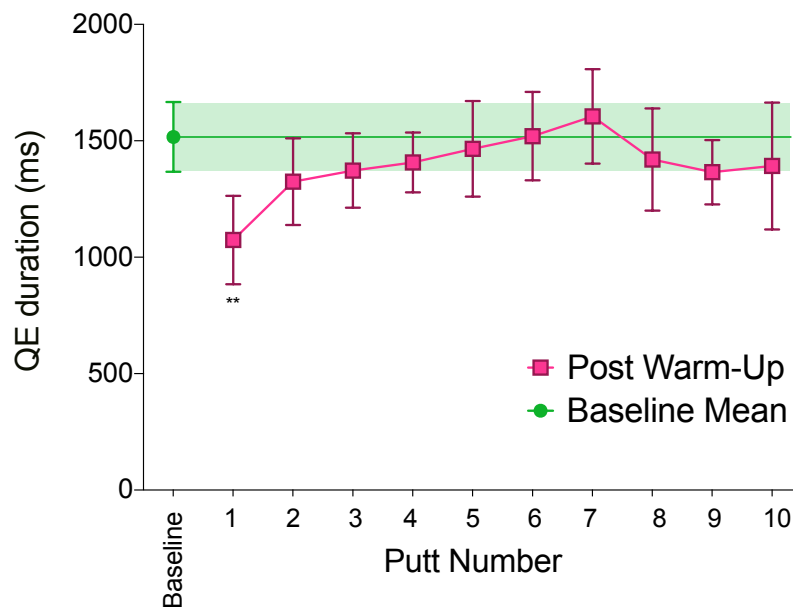

222

223   *Figure 2*. Putting radial error (mean and standard error) at baseline and across the 10 putts

224   following the VR warm up. **significantly different from baseline.

225

226   **QE period.** There was no overall difference in QE duration between putts at baseline

227   (M=1516.8 SD=634.8) and putts following VR practice (M=1380.1 SD=593.7), $t(15)=1.14$,

228    $p=.27$, $d=0.29$, $BF_{10}=0.45$. There was, however, a significant reduction in QE on the first putt

229   following VR practice (M=1073.9 SD=803.7) when compared to average baseline putts

230   (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

231   significant, we also tested the second putt, while correcting for multiple comparisons. There

232   was no significant difference between baseline QE and the second post-test putt (M=1324.46

233   SD=790.07), $t(12)=1.58$, $p=.28$, $d=.44$, $BF_{10}=0.76$, so no additional tests were run.

234

235   *Figure 3*. QE durations (mean and standard error) at baseline and across the 10 putts

236   following the VR warm up. **significantly different from baseline.

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239

14

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-

288   tests where they completed an additional 10 putts in both VR and real-world conditions (in a

289   counterbalanced order, with a 5 minute break).

290   **Data Analysis**

291   Statistical analysis was performed in JASP (v0.9.2; JASP team, 2018). Data were

292   checked for homogeneity of variance (Levene's test), and skewness and kurtosis. Performance

293   data (individual putts) exceeding three standard deviations from the mean were excluded. Gaze

294   data for nine participants (one in the VR group and eight in the RW group) were removed due

295   to poor tracking. A 2 (Training group: real-world vs VR) x 2 (Test: pre vs post) mixed ANOVA

296   was run on radial error scores (VR and real-world) and QE durations to compare the two groups

297   pre and post training. Cohen's d effect sizes were calculated for all t-tests, and partial eta

298   squared for all F-tests. Additionally, to aid the interpretation of null effects, Bayes Factors were

299   calculated using JASP (van Doorn et al., 2019). All data are available through the Open Science

300   Framework (https://osf.io/dchgz/).

301   **Results**

302   **Performance.** To examine the effect of training on putting accuracy in the real-world,

303   a 2 (group) x 2 (test) mixed ANOVA was run on radial error scores (Figure 4). Overall there

304   was a significant improvement in putting accuracy after training, (i.e. a main effect of test:

305    $F(1,38)=9.90$, $p=.003$, $\eta_p^2=.21$, $BF_{10}=11.92$), but no difference between groups,

306    $F(1,38)=0.30$, $p=.59$, $\eta_p^2=.01$, $BF_{10}=0.43$ and no interaction, $F(1,38)=0.01$, $p=.92$, $\eta_p^2=.00$,

307    $BF_{10}=0.30$.

308
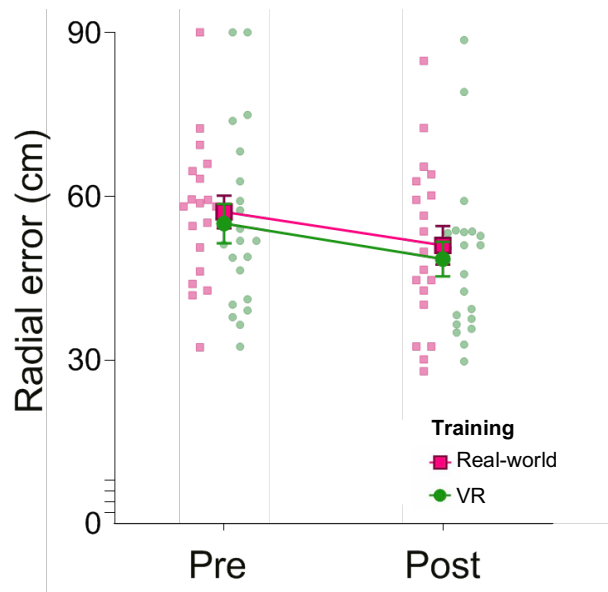
Figure 4. Radial error scores of VR and real-world trained groups on the real-world putting

task. Individual data points are shown overlaid on group-mean scores, with error bars

indicating standard error of the mean.

312

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, $F(1,38)=0.02$, $p=.89$, $\eta_p^2=.00$, $BF_{10}=.23$ and no

overall difference between groups, $F(1,38)=1.11$, $p=.30$, $\eta_p^2=.03$, $BF_{10}=.42$. As there was a

significant interaction effect, $F(1,38)=5.32$, $p=.03$, $\eta_p^2=.12$, $BF_{10}=3.35$, 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
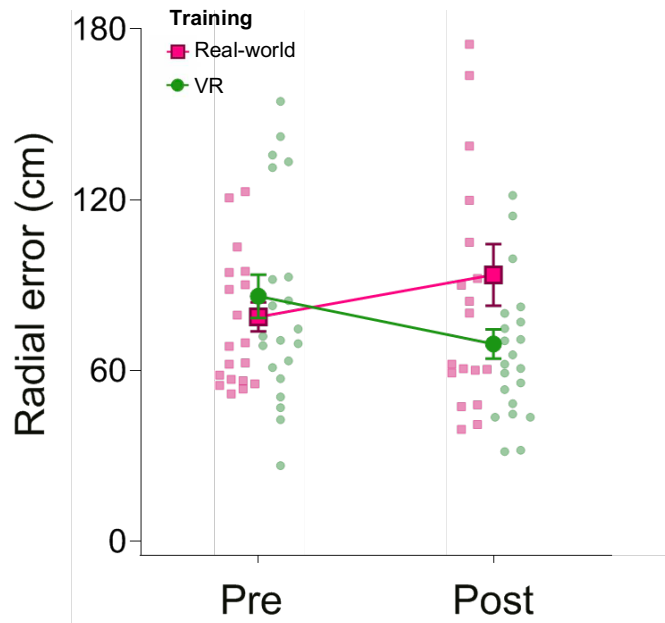
group, $t(20)=2.77$, $p=.024$, $d=.61$, $BF_{10}=4.40$.

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, $F(1,28)=0.16$, $p=.69$, $\eta_p^2=.01$, $BF_{10}=0.27$, no difference between groups, $F(1,28)=0.24$, $p=.63$, $\eta_p^2=.01$, $BF_{10}=0.40$, and no interaction, $F(1,28)=0.10$, $p=.75$, $\eta_p^2=.00$, $BF_{10}=0.36$.
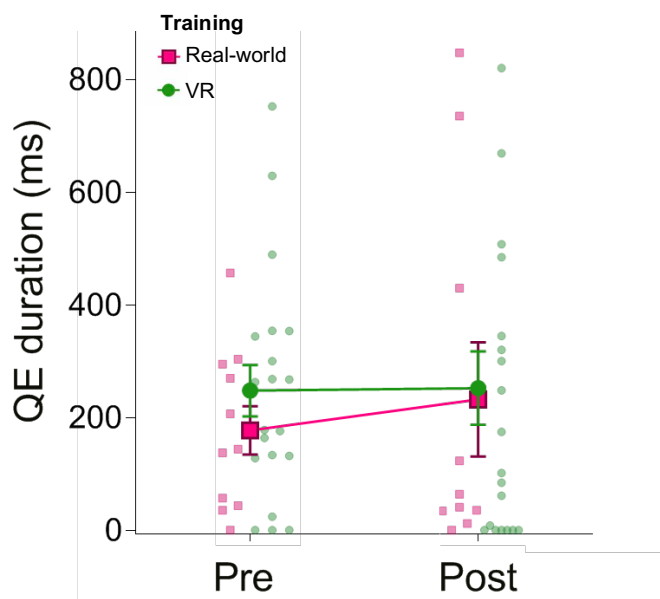
334 *Figure 6*. Mean QE durations of VR and real-world trained groups during the real-world

335 putting task. Error bars represent standard error

336 **Discussion**

337   We aimed to examine whether invariant features of the skill of putting could be

338 trained using VR, enabling skill transfer. In line with our primary hypothesis, both real-world

339 and VR putting training induced large improvements in real putting accuracy at post-test. A

340 similar level of improvement was seen between real-world (10.7%) and VR (11.9%) trained

341 groups, indicating that VR training was as effective as the causal comparator, real-world

342 training.

343   In contrast to our prediction that both groups would also improve their VR putting

344 performance, only the VR-trained group showed improved accuracy in the simulator. The

345 real-world trained group showed a non-significant decrement in performance (*d*=.27; see

346 Figure 5). The transfer of skills from VR to the real-world but not in the opposite direction is

347 consistent with the well-established phenomenon of 'dual adaptation' where adaption to a

348 sensory arrangement is more rapid after repeated experience (Welch, Bridgeman, Williams et

349   al. 1998). Dual adaptation predicts that participants would adapt faster to the addition of

350   haptic information (as this is the predominant experience) than its removal.

General discussion

352   While VR holds much promise for training, there is currently a limited understanding

353   of how VR might be best implemented to augment performance. In Experiment 1, we show

354   that VR rehearsal can have a potentially detrimental effect in expert golfers with finely tuned

355   putting skills, possibly owing to the subtle visual and haptic differences between the real and

356   virtual skill. In Experiment 2, we show that the same VR environment can be a powerful tool

357   for helping novice learners acquire an understanding of the fundamental structure of a task,

358   and demonstrate that this learning can positively transfer to real-world performance.

359   Together, these results point to a nuanced interpretation on the value of VR-based training for

360   skill acquisition, and we discuss the implications of these results.

361   Despite the disruptive effects observed in Experiment 1, the benefits of VR training in

362   Experiment 2 support the predictions of structural learning theories (Braun et al., 2010) and

363   suggest that VR can be an effective tool for visuomotor skill learning, if used in the right

364   way. Structural learning accounts explain the transfer of motor skills to new tasks, and

365   suggest that learning a related skill (i.e. the VR version in this case) can reduce the

366   dimensionality of the movement space that must be searched when moving to a new task.

367   Even though there were differences between the real and VR putting tasks, practise of the

368   putting skill in VR may have allowed the extraction of invariants that helped the subsequent

369   performance of the real skill. Consequently, effective uses of VR may well include learning

370   simple invariant features (e.g. limb coordination for the golf swing) during early stages of

371   learning, but are unlikely to include refinement of already well-learned skills.

372   Thanks to rapid advancements in immersive technologies, it is now possible to create

373   computer-generated training environments with high fidelity and face validity at increasingly

374   low price points. However, far from being a panacea for skill acquisition, there are potentials

375   risks and pitfalls that come from poor implementation of 'training' that will provide little

376   benefit (and indeed, may prove detrimental to learning). There is a requirement to test the

377   costs and benefits of specific systems and consider the skills being trained if we are to take

378   advantage of these technological advances to train athletes. Consider, for example, the impact

379   of the subtle disparity in weight between the real and VR tracked putters (400g vs 490g) in

380   our experiments. This difference (owing to the addition of a sensor on the putter head) altered

381   the putter's moment of inertia. The impact of this difference on novices appears to be

382   negligible, but for our experienced golfers, putting accuracy was disrupted (albeit

383   transiently).

384   It should also be borne in mind that the positive training effects observed in

385   Experiment 2 occurred for participants at a very early stage of learning. It is reasonable to

386   expect that the benefits of greater specificity in real-world training (Proteau, 1992) might

387   become evident over an extended training period. As studies to date have largely employed

388   similarly brief training interventions, we suggest future work should examine extended

389   training durations. It should also be noted that while we observed performance improvement

390   as a result of VR training in Experiment 2 there was no accompanying improvement in

391   perceptual skill, which may take more time to develop. Finally, to further our understanding

392   of whether skills learned in VR are fundamentally the same as those learned in the real-world,

393   the impact of concurrent tasks and performance pressure should be explored.

394

395

396 **Conclusion**

397   VR approaches have huge potential to provide novel training solutions for sports skill

398 acquisition. However, there needs to be a careful examination of the costs and benefits of

399 specific systems and a consideration of the skills being trained prior to the implementation of

400 these technologies in an athlete's training regime.

401

402   **References**

403   Al-Saud, L. M., Mushtaq, F., Allsop, M. J., Culmer, P. C., Mirghani, I., Yates, E., Keeling, A., Mon-

404   Williams, M. A., & Manogue, M. (2017). Feedback and motor skill acquisition using a haptic

405   dental simulator. *European Journal of Dental Education*, *21*(4), 240–247.

406   https://doi.org/10.1111/eje.12214

407   Bingham, G. P., Bradley, A., Bailey, M., & Vinner, R. (2001). Accommodation, occlusion, and

408   disparity matching are used to guide reaching: A comparison of actual versus virtual

409   environments. *Journal of Experimental Psychology: Human Perception and Performance,*

410   *27*(6), 1314-1334. https://doi.org/10.1037/0096-1523.27.6.1314

411   Bird, J. M. (2019). The use of virtual reality head-mounted displays within applied sport psychology.

412   *Journal of Sport Psychology in Action*, *0*(0), 1–14.

413   https://doi.org/10.1080/21520704.2018.1563573

414   Braun, D. A., Mehring, C., & Wolpert, D. M. (2010). Structure learning in action. *Behavioural Brain*

415   *Research*, *206*(2), 157–165. https://doi.org/10.1016/j.bbr.2009.08.031

416   Brookes, J., Warburton, M., Alghadier, M., Mon-Williams, M., & Mushtaq, F. (2019). Studying

417   human behavior with virtual reality: The Unity Experiment Framework. *Behavior Research*

418   *Methods, 1-9*. https://doi.org/10.3758/s13428-019-01242-0

419   Burdea, G. C., & Coiffet, P. (2003). *Virtual Reality Technology*. John Wiley & Sons.

420   Calatayud, D., Arora, S., Aggarwal, R., Kruglikova, I., Schulze, S., Funch-Jensen, P., & Grantcharov,

421   T. (2010). Warm-up in a virtual reality environment improves performance in the operating

422   room. *Annals of Surgery*, *251*(6), 1181–1185.

423   https://doi.org/10.1097/SLA.0b013e3181deb630

424   Craig, C. (2013). Understanding perception and action in sport: How can virtual reality technology

425   help? *Sports Technology*, *6*(4), 161–169. https://doi.org/10.1080/19346182.2013.855224

426   Düking, P., Holmberg, H.-C., & Sperlich, B. (2018). The Potential Usefulness of Virtual Reality

427   Systems for Athletes: A Short SWOT Analysis. *Frontiers in Physiology*, *9*.

428   https://doi.org/10.3389/fphys.2018.00128

429   Eadie, A. S., Gray, L. S., Carlin, P., & Mon-Williams, M. (2000). Modelling adaptation effects in

430   vergence and accommodation after exposure to a simulated Virtual Reality stimulus.

431   *Ophthalmic and Physiological Optics*, *20*(3), 242–251.

432   Frederiksen, J. G., Sørensen, S. M. D., Konge, L., Svendsen, M. B. S., Nobel-Jørgensen, M., Bjerrum,

433   F., & Andersen, S. A. W. (2019). Cognitive load and performance in immersive virtual reality

434   versus conventional virtual reality simulation training of laparoscopic surgery: A randomized

435   trial. *Surgical Endoscopy*. https://doi.org/10.1007/s00464-019-06887-8

436   Gray, R. (2017). Transfer of training from virtual to real baseball batting. *Frontiers in Psychology*, *8*.

437   https://doi.org/10.3389/fpsyg.2017.02183

438   Gray, R. (2019). Virtual environments and their role in developing perceptual-cognitive skills in

439   sports. In *A.M. Williams & R.C. Jackson (Eds.) Anticipation and Decision Making in Sport*.

440   Taylor & Francis, Routledge. https://doi.org/10.4324/9781315146270-19

441   Hackney, B. C., Awaad, M. F., Del Cid, D. A., Mosher, R. L., Kangavary, A., & Drew, S. A. (2018).

442   Impact of virtual reality headset use on ocular function and subjective discomfort. *Society for*

443   *Neuroscience Conference, San-Diego*.

444   Harris, D., Buckingham, G., Wilson, M., Brookes, J., Mushtaq, F., Mon-Williams, M., & Vine, S. J.

445   (2019). *Testing the fidelity and validity of a virtual reality golf putting simulator* [Preprint].

446   PsyArXiv. https://doi.org/10.31234/osf.io/j2txe

447   Harris, D. J., Buckingham, G., Wilson, M. R., & Vine, S. J. (2019). Virtually the same? How

448   impaired sensory information in virtual reality may disrupt vision for action. *Experimental*

449   *Brain Research*, *237*(11), 2761–2766. https://doi.org/10.1007/s00221-019-05642-8

450   JASP team. (2018). *JASP (version 0.9)[computer software]. Amsterdam, NLD: University of*

451   *Amsterdam.*

452   Karlsson, P., & Bergmark, A. (2015). Compared with what? An analysis of control-group types in

453   Cochrane and Campbell reviews of psychosocial treatment efficacy with substance use

454   disorders. *Addiction*, *110*(3), 420–428. https://doi.org/10.1111/add.12799

455   Kramida, G. (2016). Resolving the Vergence-Accommodation Conflict in Head-Mounted Displays.

456   *IEEE Transactions on Visualization and Computer Graphics*, *22*(7), 1912–1931.

457   https://doi.org/10.1109/TVCG.2015.2473855

458   Lammfromm, R., & Gopher, D. (2011). Transfer of skill from a virtual reality trainer to real juggling.

459   *BIO Web of Conferences*, *1*, 00054. https://doi.org/10.1051/bioconf/20110100054

460   Lebeau, J.-C., Liu, S., Sáenz-Moncaleano, C., Sanduvete-Chaves, S., Chacón-Moscoso, S., Becker, B.

461   J., & Tenenbaum, G. (2016). Quiet Eye and performance in sport: A meta-analysis. *Journal of*

462   *Sport and Exercise Psychology*, *38*(5), 441–457. https://doi.org/10.1123/jsep.2015-0123

463   Moldovanu, R., Târcoveanu, E., Dimofte, G., Lupaşcu, C., & Bradea, C. (2011). Preoperative Warm-

464   Up Using a Virtual Reality Simulator. *JSLS : Journal of the Society of Laparoendoscopic*

465   *Surgeons*, *15*(4), 533–538. https://doi.org/10.4293/108680811X13176785204409

466   Mon-Williams, M., Wann, J. P., & Rushton, S. (1993). Binocular vision in a virtual world: Visual

467   deficits following the wearing of a head-mounted display. *Ophthalmic and Physiological*

468   *Optics*, *13*(4), 387–391. https://doi.org/10.1111/j.1475-1313.1993.tb00496.x

469   Moore, L. J., Vine, S. J., Cooke, A., Ring, C., & Wilson, M. R. (2012). Quiet eye training expedites

470   motor learning and aids performance under heightened anxiety: The roles of response

471   programming and external attention. *Psychophysiology*, *49*(7), 1005–1015.

472   https://doi.org/10.1111/j.1469-8986.2012.01379.x

473   Mosher, R. L., Lundqvist, S., Morales, R., Armendariz, J., Hackney, B. C., & Drew, S. A. (2018).

474   Examining Changes in Oculomotor Function After Immersive Virtual Reality Use. *Society for*

475   *Neuroscience Conference, San-Diego*.

476   Neumann, D. L., Moffitt, R. L., Thomas, P. R., Loveday, K., Watling, D. P., Lombard, C. L.,

477   Antonova, S., & Tremeer, M. A. (2018). A systematic review of the application of interactive

478   virtual reality to sport. *Virtual Reality*, *22*(3), 183–198. https://doi.org/10.1007/s10055-017-

479   0320-5

480   Pike, T. W., Pathak, S., Mushtaq, F., Wilkie, R. M., Mon-Williams, M., & Lodge, J. P. A. (2017). A

481   systematic examination of preoperative surgery warm-up routines. *Surgical Endoscopy*,

482   *31*(5), 2202–2214. https://doi.org/10.1007/s00464-016-5218-x

483 Proteau, L. (1992). Chapter 4 On The Specificity of Learning and the Role of Visual Information for

484   Movement Control. In L. Proteau & D. Elliott (Eds.), *Advances in Psychology* (Vol. 85, pp.

485   67–103). North-Holland. https://doi.org/10.1016/S0166-4115(08)62011-7

486 Raw, R. K., Wilkie, R. M., White, A., Williams, J. H. G., & Mon-Williams, M. (2015). The

487   'Goldilocks Zone': Getting the Measure of Manual Asymmetries. *PLoS ONE*, *10*(5).

488   https://doi.org/10.1371/journal.pone.0128322

489 Ross-Stewart, L., Price, J., Jackson, D., & Hawkins, C. (2018). A Preliminary Investigation into the

490   Use of an Imagery Assisted Virtual Reality Intervention in Sport. *Journal of Sports Science*,

491   *6*(1). https://doi.org/10.17265/2332-7839/2018.01.003

492 Shafizadeh, M., McMorri, T., & Sproule, J. (2011). Effect of Different External Attention of Focus

493   Instruction on Learning of Golf Putting Skill. *Perceptual and Motor Skills*, *113*(2), 662–670.

494   https://doi.org/10.2466/05.23.25.PMS.113.5.662-670

495 Sigrist, R., Rauter, G., Marchal-Crespo, L., Riener, R., & Wolf, P. (2015). Sonification and haptic

496   feedback in addition to visual feedback enhances complex motor task learning. *Experimental

497   Brain Research*, *233*(3), 909–925. https://doi.org/10.1007/s00221-014-4167-7

498 Thorndike, E. (1906). *The Principles of Teaching*. New York:Seiler.

499 Tieri, G., Morone, G., Paolucci, S., & Iosa, M. (2018). Virtual reality in cognitive and motor

500   rehabilitation: Facts, fiction and fallacies. *Expert Review of Medical Devices*, *15*(2), 107–117.

501   https://doi.org/10.1080/17434440.2018.1425613

502 Tirp, J., Steingröver, C., Wattie, N., Baker, J., & Schorer, J. (2015). Virtual realities as optimal

503   learning environments in sport – A transfer study of virtual and real dart throwing.

504   *Psychological Test and Assessment Modeling*, *57*(1), 13.

505 van Doorn, J., van den Bergh, D., Bohm, U., Dablander, F., Derks, K., Draws, T., Evans, N. J.,

506   Gronau, Q. F., Hinne, M., Kucharský, Š., Ly, A., Marsman, M., Matzke, D., Raj, A.,

507   Sarafoglou, A., Stefan, A., Voelkel, J. G., & Wagenmakers, E.-J. (2019). *The JASP

508   Guidelines for Conducting and Reporting a Bayesian Analysis* [Preprint]. PsyArXiv.

509   https://doi.org/10.31234/osf.io/yqxfr

510   Vickers, J. N. (1996). Visual control when aiming at a far target. *Journal of Experimental*

511   *Psychology: Human Perception and Performance*, *22*(2), 342–354.

512   https://doi.org/10.1037/0096-1523.22.2.342

513   Vickers, J. N. (2007). *Perception, cognition, and decision training: The quiet eye in action.* Human

514   Kinetics.

515   Vignais, N., Bideau, B., Craig, C., Brault, S., Multon, F., Delamarche, P., & Kulpa, R. (2009). Does

516   the Level of Graphical Detail of a Virtual Handball Thrower Influence a Goalkeeper's Motor

517   Response? *Journal of Sports Science & Medicine*, *8*(4), 501–508.

518   Walters-Symons, R., Wilson, M., Klostermann, A., & Vine, S. (2018). Examining the response

519   programming function of the Quiet Eye: Do tougher shots need a quieter eye? *Cognitive*

520   *Processing*, *19*(1), 47–52. https://doi.org/10.1007/s10339-017-0841-6

521   Wann, J. P., Rushton, S., & Mon-Williams, M. (1995). Natural problems for stereoscopic depth

522   perception in virtual environments. *Vision Research*, *35*(19), 2731–2736.

523   Welch, R. B., Bridgeman, B., Williams, J. A., & Semmler, R. (1998) Dual adaptation and adaptive

524   generalization of the human vestibulo-ocular reflex. *Perception & Psychophysics 60*, 1415–

525   1425 (1998). https://doi.org/10.3758/BF03208002

526   White, A. D., Giles, O., Sutherland, R. J., Ziff, O., Mon-Williams, M., Wilkie, R. M., & Lodge, J. P.

527   A. (2014). Minimally invasive surgery training using multiple port sites to improve

528   performance. *Surgical Endoscopy*, *28*(4), 1188–1193. https://doi.org/10.1007/s00464-013-

529   3307-7

530   Wijeyaratnam, D. O., Chua, R., & Cressman, E. K. (2019). Going offline: Differences in the

531   contributions of movement control processes when reaching in a typical versus novel

532   environment. *Experimental Brain Research*. https://doi.org/10.1007/s00221-019-05515-0

533   Yamada-Rice, D., Mushtaq, F., Woodgate, A., Bosmans, D., Douthwaite, A., Douthwaite, I., Harris,

534   W., Holt, R., Kleeman, D., Marsh, J., Milovidov, E., Mon Williams, M., Parry, B., Riddler,

535   A., Robinson, P., Rodrigues, D., Thompson, S., & Whitley, S. (2017, September 12).

536   *Children and Virtual Reality: Emerging Possibilities and Challenges* [Printed Publication].

537   http://digilitey.eu/wp-content/uploads/2015/09/CVR-Final-PDF-reduced-size.pdf