Interactive Virtual Reality Reduces Quadriceps Pain during High-Intensity Cycling

CARLY L. A. WENDER1, SUN JOO AHN2, and PATRICK J. O’CONNOR1
1Department of Kinesiology, University of Georgia, Athens, GA; and 2Grady College of Journalism and Mass Communication, University of Georgia, Athens, GA

ABSTRACT

WENDER, C. L. A., S. J. AHN, AND P. J. O’CONNOR. Interactive Virtual Reality Reduces Quadriceps Pain during High-Intensity Cycling. Med. Sci. Sports Exerc., Vol. 51, No. 10, pp. 2088–2097, 2019. Purpose: Brief, high-intensity cycling is popular because physiological benefits accrue with a short workout time, but burning pain in the quadriceps is a potential barrier to engaging in this type of exercise. Virtual reality (VR) can temporarily decrease pain, but its effect on muscle pain during high-intensity exercise is unknown. The primary purpose of this experiment was to test whether adding interactive VR (I-VR) to high-intensity cycling could reduce quadriceps pain or improve performance. Methods: Ninety-four adults who were physically active in their leisure time and age 18 to 29 yr completed three 30-s sprint interval cycling trials at a high resistance (0.085- and 0.075-kg resistance to the flywheel per kilogram body weight for men and women, respectively). In this randomized between-subject experiment, participants cycled while wearing a head-mounted display and viewing either (i) a dynamically changing cityscape perceived as interactively cycling through a virtual city (I-VR group) or (ii) a static picture of the cityscape with instructions to mentally imagine cycling through that city (static VR/motor imagery control group). Results: Sphericity-adjusted 2 × 3 (group–time) ANOVA revealed a significant group–time interaction (F = 4.568, df = 1.499, 133.301; ηp2 = 0.047, P = 0.021) for pain intensity. With I-VR, pain intensities were 13.3% (mean, 4.60 vs 5.31; d = 0.28) and 11.8% (mean, 5.68 vs 6.44; d = 0.27) lower at sprint trials 2 and 3, respectively. The group–time interaction (P = 0.412) was not significant for total work. Conclusion: Compared with a static VR/motor imagery control condition, I-VR during brief, high-intensity, fatigue-inducing leg cycling attenuates quadriceps pain intensity without reducing performance. Key Words: FATIGUE, SPRINT INTERVAL TRAINING, PAIN INTENSITY, PERCEIVED EXERTION, VR

High-intensity interval training (HIIT) and sprint interval exercise (SIE) have become popular fitness activities because healthful cardiometabolic adaptations can accrue with short workout durations (1). Nevertheless, only approximately 51% of US adults engage in sufficient regularly activity to meet federal physical activity guidelines recommended for health. Thus, there continues to be a need for evidence-based methods to reduce barriers to engaging in physical activity, including HIIT and SIE. Most HIIT and sprint interval training (SIT) protocols use stationary leg cycling, which produces feelings of fatigue and quadriceps pain, two potential barriers to tolerating and engaging in this type of training (2). If exercise-induced quadriceps muscle pain and feelings of fatigue could be reduced, then more people may be willing to adhere to HIIT and SIE.

Distraction, or diverting an individual’s attention away from something, has hypoalgesic effects during some medical procedures, but its effects on pain in active skeletal muscles during exercise are less clear (3). Greater attentional and physical demands of performing high-intensity exercise likely make traditional distraction techniques less effective pain relievers during HIIT and SIE (4). Virtual reality (VR), especially that involving interaction in a simulated environment, has greater potential to engage limited attentional resources and therefore may be more likely to reduce HIIT- and SIE-induced quadriceps pain during stationary cycling (5). VR-based interventions can attenuate acute pain among burn patients (6) and can improve feelings of energy and fatigue in response to moderate-intensity exercise (7), but whether these benefits occur during painful, high-intensity, acute exercise is unknown. VR has also been shown to be associated with improved cycling performance in two previous studies (8,9), but it is unclear if those improvements resulted from the addition of VR or from other factors that co-occurred with VR, such as social facilitation via the simulated presence of competitors.

VR may produce the greatest distraction and pain relief when the simulation demands more attentional resources (10). VR increases visual load, which can attenuate the perception of competing stimuli, and may attenuate pain threshold, although this has not been studied extensively in the context of exercise (11). Interactive VR (I-VR) added to stationary cycling not only increases the attentional demand but also provides a specific type of visual cue typically missing—optical flow, the visual
motion we perceive when our bodies move through a real environment while, for example, driving or cycling (12). VR is unique in that it provides stereoscopic view and a head-controlled point of view, which heightens a person’s sense of optical flow. The effect of manipulating optical flow using VR on exercise-induced muscle pain intensity is understudied. The addition of optical flow to cycling may increase feelings of presence (13), the perception of “being there” in a virtual world, which has been found to negatively relate to pain intensity and positively correlate with an increase in pain threshold and pain relief in nonexercise settings (14).

The primary purpose of this experiment was to examine the effect of I-VR on changes in quadriceps pain intensity and cycling performance during a single SIT session. To isolate the effects of optical flow provided by I-VR, a control group completed the same acute exercise task and used the same head-mounted display (HMD), which visually presented a single, static scene from the I-VR condition. This scene was static and therefore did not involve interaction with the virtual environment or optic flow. Concerns over the incongruity of viewing a static scene during actual cycling (e.g., simulation sickness) contributed to our decision to add motor imagery, the act of mentally imagining physical movement, to this control condition. By instructing participants to imagine themselves moving through the city scene depicted before them, there was agreement with the physical movement of their body on the cycle ergometer. We hypothesized that, compared with the static VR/motor imagery control group, the I-VR group would show better performance and report increasingly less pain intensity in response to three brief high-intensity cycling bouts. As a secondary aim, we also evaluated the potential influence of several variables that could plausibly moderate the effects of I-VR on pain and cycling performance, including changes in feelings of energy and fatigue, recent leisure time physical activity (LTPA), baseline level of cycling performance, biological sex, perceived exertion, time of day of testing, and knowledge of the primary purposes of the experiment. Exploratory information was obtained about relationships among pain, performance, and feelings of presence in an immersive and interactive virtual environment.

METHODS

Participant Recruitment and Screening

Participants were recruited through campus flyers, listservs, course announcements, and word-of-mouth conversations between October 1, 2017, and April 1, 2018. Eligibility requirements included that participants (i) not be younger than 18 yr or older than 29 yr; (ii) not have any contraindications to high-intensity exercise, as indicated by the Physical Activity Readiness Questionnaire; (iii) not have a body mass index (BMI) <18 or >35 kg·m⁻², based on self-report; (iv) not use prescription medication of any kind, based on self-report; (v) not wear eye glasses during exercise; and (vi) not have a high likelihood of motion sickness. Likelihood of motion sickness was measured with one item in the screening questionnaire: “How likely are you to experience motion sickness (when riding in a car as an example)?” Potential participants responded on a 1 (extremely likely) to 5 (extremely unlikely) Likert-type scale. Any potential participant who answered “extremely likely” was excluded from testing. Eligible volunteers signed an informed consent approved by the institutional review board at the University of Georgia. Compensation, in the form of class credit, was granted to students in participating classes once both testing sessions were completed. No other form of compensation was provided.

Research Design

This study used a mixed-model experimental design; the between factor was the experimental group (I-VR) compared with static VR with motor imagery (CONTROL) and the within factor was time (i.e., cycling exercise trials 1, 2, and 3). A random number generator in Microsoft® Excel 2010 was used to assign participants to conditions. Researchers administering the testing sessions were not blinded to the group assignment but used minimal, similar social interactions to minimize potential biases.

Cycling Exercise

Participants were instructed to avoid food for 2 h and caffeine for 6 h before the exercise tests. As is common in SIE experiments, several consecutive Wingate tests were administered. The Wingate test consisted of a maximal effort leg exercise involving a 30-s sprint on an electronically braked cycle ergometer (Lode Excalibur) against a high resistance (0.085- and 0.075-kg resistance to the flywheel per kilogram body weight for men and women, respectively). The resistance was calculated and applied by computer software (Wingate Lode program, version 1.0.11). Participants warmed up for 5 min at a very low intensity (20 W). Approximately 10 s before the resistance increased, participants were instructed to begin pedaling faster. Once the full resistance was applied, participants were verbally encouraged in a standard fashion by the test administrator to give a maximal effort throughout the entire 30-s sprint. Participants then pedaled at 20 W for 4 min of active recovery. This protocol of sprint and recovery was repeated two times. Participants were familiarized with this protocol at least 1 wk before the testing session.

Primary Outcome Measures

Pain intensity. Pain intensity was measured immediately after each 30-s sprint using a well-validated 0–10 category scale with ratio properties (15). Before the exercise test, standardized instructions were provided verbally, and it was emphasized that the focus should be on pain intensity perceived in the activated quadriceps muscles (15). Every participant was asked to rate the peak pain intensity in their quadriceps as soon as each sprint concluded.

Cycling performance. Cycling performance was quantified from the total work performed during each 30-s Wingate test. Total work (in joules) was measured from the constant resistance and changing velocity of the flywheel of the cycle ergometer. Resistance and flywheel data were interfaced with a
Covariates

**Feelings of energy and fatigue.** Energy and fatigue mood states were used as potential moderators based on the idea that pain relief with VR may be more effective when co-occurring with positive affect. Four aspects of energy and fatigue feelings were measured using the Mental and Physical State Energy and Fatigue scales: physical energy, physical fatigue, mental energy, and mental fatigue. Each scale consists of three items that use a 10-cm visual analog format. In relation to their perceived capacity to perform typical mental, and separately physical, activities, participants rated their “right now” feelings of energy, vigor, pep, fatigue, exhaustion, and being worn out. Scores on each three-item scale were summed to yield criterion scores. Energy and fatigue levels were measured at three time points: before the exercise test and approximately 7 and 15 min after the final sprint. Postexercise (15 min) minus preexercise change scores were used in the analysis. Published data support the validity of these scales, including their sensitivity to change in response to acute exercise (16). The scales and a manual are available from the authors.

**Leisure time physical activity.** LTPA was used as a potential moderator because of the evidence that LTPA is negatively associated with pain and sensitivity to painful stimuli. LTPA was measured using the Godin Leisure Time Physical Activity Questionnaire. Participants indicated the number of times during the prior 7-d period they spent 15 min or more doing strenuous, moderate, or mild exercise. Total weekly LTPA scores were calculated as recommended using estimated resting metabolic rate equivalents (METs) as follows: (strenuous bouts × 9 METs) + (moderate bouts × 5 METs) + (mild bouts × 3 METs). Based on this scale, it has been suggested that people who report less than 24 units are insufficiently active, while those who report 24 units or greater are active (17).

**Baseline level of cycling performance and biological sex.** Baseline cycling performance (total work during each of the three Wingate sprint trials in the familiarization session) was used as a potential moderator because when groups cycle with the same load relative to their maximum (i.e., a group of women and a group of men both cycling at 80% of peak power output), those with the higher absolute load report higher leg muscle pain intensity (18). Men were given a higher load in the present study because, on average, they produce higher peak power outputs. Sex-related differences in pain and several biological systems related to pain are well recognized (18). Thus, the potential moderating influence of biological sex was considered separately.

**Perceived exertion.** Perceived exertion, a recognized index of the feedforward central nervous system signals that activate musculature during exercise, was used as a potential moderator because pain intensity ratings could influence how fully the central nervous system activates the leg muscle during cycling. RPE values were obtained immediately after each of the three pain intensity ratings using Borg’s 0–10 RPE scale (19). Standardized verbal instructions were used to ensure that the participants understood the difference between perceptions of pain and effort and that effort ratings should focus on overall perceptions, not solely on leg perceptions (15). Each participant was asked to rate their level of perceived exertion immediately after their pain intensity rating immediately after each sprint.

**Time of day.** Time of day was used as a potential moderator because of the evidence that exercise performance, as well as both pain ratings and pain modulation processes (20), depends in part on circadian processes. The time of day variable was dichotomized into morning (8 AM–11:59 AM) versus afternoon (12 PM–6 PM) testing sessions. No evening or overnight testing sessions were conducted.

**Knowledge of the purpose of the experiment.** Knowledge of the purpose of the experiment was used as a potential moderator to test whether that knowledge biased the participants’ behavior (i.e., cycling performance) or pain intensity reports. At the end of the experiment, all participants were asked a single open-ended question: “What do you think the purpose of this experiment was?” These responses were coded to identify those who did not know the purpose, those who thought the purpose was to use VR to influence pain, and those who contended that the purpose was to use VR to influence cycling performance.

**Spatial Presence in the VR Environment**

Spatial presence is the subjective feeling of having authentically visited a mediated location, wherein users temporarily forget the fact that they are in a simulated environment (13). This can be achieved by surrounding users with rich layers of sensory information that are often perceived as if the individual is experiencing a physical world. When perceiving high spatial presence, the user cognitively perceives that the physical body genuinely exists in the simulated space (immersion) and is in sync with the movements of the virtual experience (interactive). Spatial presence has been hypothesized to be a moderator of pain relief in experiments that have examined the influence of VR on pain. We used a five-item, 7-point Likert scale to measure perceived spatial presence based on prior immersive VR research (21,22), but adapted the wording to be specific to the context of our intervention. Specifically, “objects” and “virtual shower” were replaced by “virtual city” to better represent our virtual environment. The five items were as follows: “I felt surrounded by the virtual city,” “I felt like I really visited the city,” “I felt like I really visited the city,” “The city seemed like the real world,” “I felt like I could reach out and touch the objects on the city street,” and “I felt immersed in the city.” Item scores were averaged and ranged from 1.8 to 7.0. The internal consistency reliability of the five scale items was calculated in SPSS using the coefficient α technique. The reliability coefficient for the present sample was high (α = 0.91), providing evidence that the items are measuring a single construct.

**Experimental Protocol**

First session (baseline and familiarization). First, the informed consent was read, discussed with a researcher, and
signed. The aims of the experiment were purposefully described in the following nonspecific way to minimize biased responding that might happen from knowledge that the specific purposes of the investigation were to examine effects of I-VR on pain and performance: “The primary purpose of this study is to examine what happens when people imagine a scene while exercising compared with what happens when the scene is presented using virtual reality.” The consent also stated, “To get the most truthful results, some information about this study will be withheld until the study is complete.”

After completion of the informed consent process, all participants completed the baseline questionnaire. This questionnaire included demographic information, current pain information, ability to vividly visualize mental imagery, personal history of VR use, and the hours since food and caffeine were consumed. After reading the scale instructions, energy and fatigue mood states were measured. Next, a researcher measured the participant’s height and body mass to the nearest cm and 0.5 kg using a calibrated balance beam scale (Detecto Model 439). Those values were input into the Wingate software program, which calculated the resistance applied to the flywheel during the sprint. The participant self-affixed a heart rate monitor (Polar Vantage XL), then his/her shoes were tightly affixed to the pedals of the ergometer using prewrap and athletic tape. The researcher then read the instructions for the perceived pain and exertion scales that would be presented immediately after each sprint. The participants then completed the three Wingate tests without visual stimuli or wearing a VR HMD. The test administrator verbally encouraged participants to give a maximal effort throughout each 30-s sprint. At the end of the final bout of active recovery, participants rested for 2 min and completed the mood scales for a second time. Then they rested for 7 min and completed the mood scales a third time.

Second session (intervention). The second testing day took place approximately 1 wk after the first visit. The procedure was almost identical to the first session. Participants began by completing the first energy and fatigue mood scale and then self-affixing the heart rate monitor. During this visit, one of the HTC Vive controllers containing a motion sensor was taped to the participant’s right foot. Leg motions were detected from ceiling mounted optical tracking cameras (Natural Point Optitrack Optical Motion Capture System) integrated with a Dell computer, which communicated with the HMD. Both feet were affixed to the pedals of the ergometer. The instructions for the perceived pain and exertion scales were explained in an identical manner as the first session. However, it was further explained that the scales would appear in the HMD after each sprint, as opposed to being shown on paper by the researcher, as was done in the first session. Instructions were then given on how to self-affix the headset and what to expect to see. Both conditions involved immersive VR because participants were wearing an HMD, which provided several sources of sensory information, including stereovision, head-controlled point of view, and movement/body tracking. For those in the CONTROL group, participants were told that inside the HMD they would see a static picture of a city scene and they were to imagine that they were cycling through that city during the sprints. In addition, they were told, “If it helps you to close your eyes for more vivid imagery, I encourage you to do so.” For those in the I-VR group, which was interactive and immersive, participants were told that they would be immersed in a city scene that they would move through at the speed at which they pedaled. This exercise session was completed exactly as in the previous testing session, including the verbal encouragement provided by the test administrators, as were the rest periods and administrations of the last two sets of mood scales. On this final testing day, there were additional scales/questionnaires to complete after the third set of mood scales. For the I-VR group only, they completed the spatial presence scale and then a postexperiment questionnaire that asked one open-ended question: “What do you think the purpose of this experiment was?” Participants in the CONTROL group were not asked about spatial presence.

Statistical Analysis

Preliminary analyses. For any participant who experienced nausea or dizziness at any point during the study, his/her session was stopped, and his/her data were excluded from analysis (n = 8). All of the continuous variables were characterized by homogeneity of variances and a normal distribution. Independent t-tests and χ² tests were used to test for group differences at baseline.

Primary analyses. The primary hypotheses were tested using a series of 2 × 3 (group (I-VR vs CONTROL) × time (trials 1, 2, and 3)) mixed-model ANOVA. When the interaction was significant, one-way ANOVAs and independent t-tests were used as post hoc tests and secondary covariates were explored. Each covariate was added separately. The interpretation was that the covariate moderated the change in pain or performance when the addition of the covariate changed the interaction from a statistically significant F value to an insignificant F value (23). When sphericity could not be assumed based on Mauchly’s test, Huynh–Feldt ε adjustments were used. Effect size magnitudes are reported using standardized group differences d = [(mean x1 − mean x2)/SDpooled] and partial eta squared values (η²p) for interactions. A statistical power analysis, with an α error of 0.10 (Bonferroni adjusted for the two primary outcomes) and a correlation between the two repeated measures across time of r = 0.60, indicated that 45 participants in each group provided statistical power of 0.80 to detect a small effect size (η²p of 0.02) for the hypothesized group–time interaction (24). Correlations and scatterplots between presence and both pain and cycling performance were examined for exploratory purposes.

RESULTS

Participant Recruitment and Characteristics

Ninety-four participants (37 men, 57 women) were included in data analysis. Figure 1 details the flow from the 215 participants recruited to the final number tested in each group and included in data analysis. There were no significant differences in all variables measured during the baseline session between the
participants who completed both sessions of testing and those who dropped out after one session (n = 18).

Mean (SD) age and BMI were 20.91 (1.84) yr and 24.24 (3.93) kg·m⁻², respectively. There were 49 participants in the CONTROL group and 45 in the I-VR group. The demographics and baseline information of these groups are detailed in Table 1. The groups were similar on all demographic variables except BMI, which was higher (t = −2.00, df = 92, P = 0.048) in the I-VR group (mean (SD), 25.07 (4.20)) than in the CONTROL group (mean (SD), 23.47 (3.53)). During the familiarization session, only one participant in each group reported any pain in their lower body before exercise, and it was rated as 1 and 4 on the 0–10 scale. Before cycling in the intervention session, no participant reported pain resulting from the exercise performed during familiarization.

Primary Outcomes

Pain intensity. For pain intensity, a significant group–time interaction was found (F = 4.568; df = 1.499, 133.301; η²_p = 0.047; P = 0.021). Post hoc tests showed that both the I-VR (F = 48.443; df = 1.451, 63.832; η²_p = 0.524; P < 0.001) and the CONTROL (F = 109.77; df = 1.412, 67.790; η²_p = 0.524; P < 0.001) groups increased in pain intensity significantly across trials and did not differ at trial 1 (t = −0.095, P = 0.925). In the I-VR condition, pain intensity was 13.3% (mean, 4.60 vs 5.31; d = 0.28) and 11.8% (mean, 5.68 vs 6.44; d = 0.27) lower than in the CONTROL condition at trials 2 and 3, respectively. The pain intensity results are illustrated in Figure 2.

Potential covariates. Separate ANCOVAs adjusting for LTPA; sex; time of day; changes in feelings of energy and fatigue; total work at baseline trials 1, 2, or 3; and perceived exertion did not change the significance of the interaction. Twenty-one participants correctly identified the primary purpose of this experiment as investigating changes in perceived pain in response to the addition of I-VR to the cycling task. Including this variable as a covariate did not change the significance of the group–time interaction for pain intensity (F = 4.918; df = 1.460, 132.844; η²_p = 0.051; P = 0.016). The descriptive results for the covariates are presented in the Supplemental Digital
TABLE 1. Preexercise characteristics.

<table>
<thead>
<tr>
<th></th>
<th>CONTROL Group</th>
<th>I-VR Group</th>
<th>Significant Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Age, avg (SD), yr</strong></td>
<td>20.82 (1.82)</td>
<td>21.02 (1.86)</td>
<td>NS</td>
</tr>
<tr>
<td><strong>Sex, no. male/female</strong></td>
<td>18:31</td>
<td>19:26</td>
<td>NS</td>
</tr>
<tr>
<td><strong>BMI, avg (SD), kg·m⁻²</strong></td>
<td>23.47 (3.53)</td>
<td>25.07 (4.20)</td>
<td><strong>P = 0.048</strong></td>
</tr>
<tr>
<td><strong>Time of day, no. in morning/afternoon</strong></td>
<td>20:29</td>
<td>18:27</td>
<td>NS</td>
</tr>
<tr>
<td><strong>LTPA, avg (SD)</strong></td>
<td>59.65 (30.44)</td>
<td>54.14 (21.54)</td>
<td>NS</td>
</tr>
<tr>
<td><strong>Days since the end of last menstrual period (female only), avg (SD)</strong></td>
<td>27.28 (17.96)</td>
<td>23.00 (10.96)</td>
<td>NS</td>
</tr>
<tr>
<td><strong>VR experience, no. yes/no</strong></td>
<td>27:22</td>
<td>26:19</td>
<td>NS</td>
</tr>
<tr>
<td><strong>Total work during familiarization sprint 1, avg (SD)</strong></td>
<td>12,676.73 (3382.06)</td>
<td>13,611.33 (4044.30)</td>
<td>NS</td>
</tr>
<tr>
<td><strong>Total work during familiarization sprint 2, avg (SD)</strong></td>
<td>12,237.86 (3045.19)</td>
<td>12,939.33 (3952.38)</td>
<td>NS</td>
</tr>
<tr>
<td><strong>Total work during familiarization sprint 3, avg (SD)</strong></td>
<td>11,171.49 (2979.13)</td>
<td>11,780.00 (4239.46)</td>
<td>NS</td>
</tr>
<tr>
<td><strong>Preexercise physical energy, avg (SD)</strong></td>
<td>166.29 (47.59)</td>
<td>173.43 (49.74)</td>
<td>NS</td>
</tr>
<tr>
<td><strong>Preexercise physical fatigue, avg (SD)</strong></td>
<td>115.46 (63.99)</td>
<td>121.23 (67.45)</td>
<td>NS</td>
</tr>
<tr>
<td><strong>Preexercise mental energy, avg (SD)</strong></td>
<td>170.74 (47.28)</td>
<td>170.46 (60.09)</td>
<td>NS</td>
</tr>
<tr>
<td><strong>Preexercise mental fatigue, avg (SD)</strong></td>
<td>118.56 (64.65)</td>
<td>120.18 (71.20)</td>
<td>NS</td>
</tr>
</tbody>
</table>

Baseline characteristics of participants: the I-VR and static VR/CONTROL groups.

*Significant result.

Content (Table, Supplemental Digital Content 1, Relationships between pain intensity ratings and variables measured as potential moderators, http://links.lww.com/MSS/B589).

**Performance.** Figure 3 shows that the total work decreased across the three sprints for both groups (time: \( F = 96.354; df = 1.456, 133.979; \eta_p^2 = 0.512; P < 0.001 \)), and the main effect of condition (\( P = 0.396 \)) and group–time interaction (\( P = 0.412 \)) were not significant.

**Concomitants of performance.** Figure 4 shows that mean RPE increased across the three sprints for both groups from below to above the "very heavy" category; this time effect was significant (time: \( F = 103.868; df = 1.327, 122.086; \eta_p^2 = 0.530; P < 0.001 \)), whereas the group main effect (\( P = 0.905 \)) and group–time interaction (\( P = 0.462 \)) were not significant. The peak heart rate results are illustrated in Figure 5. Peak heart rate increased across the three sprints for both groups (time: \( F = 101.508; df = 1.637, 150.636; \eta_p^2 = 0.525; P < 0.001 \)), and the condition main effect (\( P = 0.292 \)) and group–time interaction (\( P = 0.412 \)) were not significant. Mean peak heart rate values during the third sprint for the I-VR (178 ± 12) and CONTROL (176 ± 10) groups were consistent with a national database providing reference standard responses to maximal cycle tests for young adults (~179 ± 15) (25).

**Exploratory Results for Presence.** Presence scores, obtained only from the I-VR group (\( n = 45 \)), were negatively related to pain intensity, and these relationships approached statistical significance from sprint one to three (\( r = -0.23 \) to \(-0.28 \) [\( P = 0.121–0.64 \)]). Presence scores were significantly and positively related to physical fatigue immediately after the final sprint (\( r = 0.46, P = 0.001 \)) but not 15 min after exercise (\( r < 0.10 \)).

**DISCUSSION**

**Primary outcomes.** The primary finding of this investigation was that, compared with a static VR/motor imagery control condition in which an HMD presented a static scene and participants mentally imagined moving through it while cycling, I-VR reduced quadriceps pain intensity caused by repeated bouts of brief, high-intensity, fatigue-inducing leg cycling in healthy adults. The magnitude of this hypoalgesia was small based on a general statistical proposition suggested by Cohen (26) but is comparable to pain relief shown in research on HIIT, the only other known method for reducing...
The present results complement the one prior study that examined the influence of I-VR on exercise-induced pain in healthy young adults (mean age, 23 yr) (29). In that investigation, muscle pain was caused by a continuous isometric biceps flexion of 20% of 1-repetition maximum until failure. Compared with a control involving the same exercise without VR, mean biceps pain intensity ratings were lower after 1 and 2 min. Potential moderators, such as biological sex, time of day of testing, or physical activity history, were not examined. Exercise performance was better in the I-VR group; however, the time to exhaustion test used is known to be significantly less reliable than exercise tests in which the participant knows the distance or duration of the exercise to be performed before starting (30). The present investigation provides the first experimental documentation of a hypoalgesic effect of I-VR during brief, high-intensity, fatigue-inducing painful cycling exercise bouts. This new information extends, to exercise-induced pain, what is known about the pain-reducing effects of VR without exercise in patients with acute and chronic pain undergoing treatment (31) or healthy adults exposed to experimentally induced thermal stimuli (32).

Studies on exercise and VR have sought to use VR to increase motivation, adherence, and performance in (i) healthy adults and children and (ii) in patients undergoing rehabilitation after an injury or illness by adding VR to cycle ergometry (33), treadmill walking (34), and indoor rowing (35). Cancer patients recovering from thoracotomy surgery (36), hemodialysis patients (37), and stroke victims (38) have all shown faster recovery with the integration of VR to typical rehabilitation programs. In contrast to the present experiment, these studies used interactive but nonimmersive VR, like Wii Fit, and pain was not measured.

**Covariates.** None of the covariates moderated the effects on pain intensity. Changes in feelings of physical energy and fatigue were most strongly related to pain intensity during the final two sprints; higher pain intensity ratings were associated with reports of less energy and greater fatigue to perform typical physical activities. Higher pain ratings during the final sprint were also associated with greater changes in feelings of mental fatigue. These novel observations are generally consistent.
with the limited amount of previous nonexercise research relating to pain and symptoms of fatigue. Quadriceps pain intensity, averaged across both conditions, did not differ between men and women at cycling trial 1 (3.53 ± 2.21 vs 3.48 ± 2.15), but was lower at trial 3 for women (6.62 ± 2.59 vs 5.72 ± 2.84). This observation is consistent with lower quadriceps pain intensity ratings in women compared with men at the end of a maximal cycling exercise test but not at the beginning of the test (18). Lower quadriceps pain intensity during cycling for women compared with men is in part a function of the lower total work performed based on experiments showing such effects when men and women are matched relative to their peak power (18).

**Presence.** As an exploratory measure, spatial presence ratings were obtained from the VR group only and therefore could not be included as a covariate. Feelings of presence were negatively correlated with pain intensity, to a magnitude that approached statistical significance. This relationship is not likely to result from greater presence causing reduced total work because the relationships between presence and total work were weak. These findings suggest that presence could plausibly mediate the effects of I-VR on exercise-induced pain. Greater presence within an environment may be more distracting than immersing oneself in an environment that may not feel quite so encompassing, such as with motor imagery, and greater distraction can have larger effects on reducing pain perception. Feelings of presence also may contribute to postexercise feelings of physical fatigue based on the positive, significant relationship between presence and fatigue immediately after exercise. There is no clear literature-based explanation for this relationship, as it seems that there is an absence of research examining relationships between presence and feelings of physical fatigue. Future studies should consider including a measure of presence in all comparison groups, which may provide insight into this potential mechanism by which I-VR could impact pain during exercise.

**Possible mechanisms.** Overwhelmingly, studies involving VR and pain cite the distracting, engaging, and reinforcing nature of immersive and I-VR as the primary mechanism of hypoalgesia. Unlike other distraction techniques, the immersion provided by I-VR provided through an HMD may be distracting enough to overcome the attention to movement and related sensory feedback required to produce and maintain high-intensity exercise (39). Even in the absence of more distracting elements, such as goal-orienting tasks and cognitive complexity (10), the relatively simple virtual environment used in this experiment elicited pain relief.

I-VR can be a powerful form of distraction because it maintains optical flow. Studies of treadmill walking have demonstrated greater perceived exertion, power output, and speed with slower optic flow (40), but the effect of optic flow on pain during exercise is understudied. Here, exercise-induced pain was attenuated significantly more in the condition that provided optical flow. Future research could better explicate this relationship by manipulating optical flow to several levels and measuring changes in exercise-induced pain.

**Simulator sickness.** Although HMD provides the most immersive form of VR, it is also most likely to cause simulator sickness or related symptoms, including dizziness and nausea, leading several exercise-related researchers to use less risky VR systems. Maximal effort Wingate cycling sprints already carry a risk of dizziness and nausea, which is why a high likelihood of experiencing motion sickness was an exclusion criterion in our study. Eight of 117 participants dropped out because of nausea or lightheadedness during the baseline cycling sprints. Only one participant who completed the exercise test with the HMD experienced related symptoms. She described the virtual environment as “flashy,” said the HMD made her feel dizzy, and noted feeling nauseated after the final sprint. This participant did feel slightly nauseated after cycling during the baseline session without the HMD but insisted on continuing the study. Newer HMD systems offer higher fidelity between virtual and physical movements, which reduces the likelihood of simulation sickness. This investigation shows that with proper precautions, investigators can safely use HMD during brief, high-intensity cycling exercise.

**Limitations.** One limitation of this experiment was the lack of direct connection between the cycle ergometer and VR program. Virtual cycling acceleration and decelerations were matched to the participant’s actual performance via optical tracking cameras detecting the movements of the controller taped to the participant’s foot. Ideally, one would have the VR program obtain information on moment-to-moment changes in acceleration directly from the cycle ergometer. Five participants noted, unprompted, that they were moving faster in VR than their perceived real-life pedal rate, especially during the warm-up. The researcher also noted this discrepancy in three participants who did not mention it.

Another limitation in this experiment was that presence measures were only taken for the I-VR group, and neither standardized motor imagery instructions were provided, nor was there any check on imagery performance obtained (e.g., imagery controllability, vividness, or internal vs external perspective).

Also, we lacked resources to include other potentially useful comparisons, such as a no-treatment control group (i.e., exercise without VR). Previous studies on exercise and VR, including the isometric biceps flexion study described earlier (29), have compared exercising with VR to no-treatment control groups. Employing a no-treatment control group is likely to lead to exaggerated and inflated effects when comparing VR with nothing. Therefore, we rejected that approach to make a stronger test of the effect of I-VR on pain by comparing it with a condition that included nonspecific effects of VR that might influence pain (e.g., wearing a HMD and viewing a static VR image that lacked optical flow). We also rejected including a group that compared exercise while exposed to static VR but without motor imagery instructions. This was done over concerns about the incongruency between actual cycling movement and the lack of either actual or imagined movement. With access to greater resources, in the future, researchers can conduct similar experiments to ours that include these comparison groups.
Lastly, testing would have to be done on a wider sample, such as older adults and those characterized by low and high cardiorespiratory fitness, using different exercise intensities and/or VR systems to better generalize the hypoalgesic effects of I-VR during exercise.

Future research. In a healthy sample of college-age participants, I-VR decreased quadriceps pain intensity during repeated, fatiguing maximal effort sprints on a stationary cycle ergometer. This hypoalgesia was found using a between-subject design, so whether this effect is reproducible across days of repeated I-VR during high-intensity cycling is unknown and deserves future research attention. Whether this effect extends to those with acute or chronic pain would also be a worthwhile future investigation. Only by testing this intervention on a clinical population could we accurately assess whether the small effect size seen here translates to clinically meaningful improvements. Regular physical activity is associated with lower rates of chronic pain, and exercise is an effective treatment for several chronic pain conditions. However, it is difficult to convince people in pain to exercise when exercise prompts greater pain. Adding I-VR to exercise may help people in pain overcome the idea that exercise is linked to more pain and subsequently increase their adherence to regular exercise, as has been found with nonimmersive VR.

The virtual environment used in the present experiment was simplistic and designed to examine a proof of concept. Future studies should manipulate the virtual environment in various ways, including increasing cognitive demand, adding goals to complete, including more positive aspects, and manipulating presence, which may ultimately show a greater effect on pain. The excitement surrounding VR stems in large part from the endless opportunities to create and manipulate virtual environments.

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