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Effectiveness of virtual and augmented reality-enhanced exercise on physical activity, psychological outcomes, and physical performance: A systematic review and meta-analysis of randomized controlled trials

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ABSTRACT

Virtual reality (VR) and augmented reality (AR)-enhanced exercise training is a novel approach to promoting health. Previous systematic reviews have focused on the effectiveness of VR interventions in clinical settings. The present study was the first systematic review to investigate the effectiveness of exercise-based VR and AR training as preventive measures in improving physical activity, psychological outcomes, and physical performance of a healthy population when compared with traditional programs and no-exercise controls. This study included 22 research articles published between 1997 and 2017, involving 1,184 participants aged 18 to 79. The results showed a large effect on physical activity (Hedges' $g = 0.83$, $SE = 0.18$), a small to moderate effect on physical performance (Hedges' $g = 0.31$, $SE = 0.09$), and no significant effect on psychological outcomes. VR training programs were particularly shown to be effective for enhancing frequency of physical activity and strength of physical performance. Only two studies examined the effectiveness of AR training programs on physical performance, and the findings concerning those effects were not separately reported. A list of plausible moderators was tested but that variable was not significantly associated with the effects of VR on the three outcomes. Limitations and future directions are discussed.

1. Introduction

While health authorities around the world have been actively promoting physical exercise in the past decades, the global prevalence of physical inactivity was found stable in the period between 2001 and 2016 (Guthold, Stevens, Riley, & Bull, 2018). About 25% of the world's adults and 80% of adolescents are physically inactive (WHO, 2018), which may be attributable to urbanization and environmental factors such as high-density traffic and lack of recreation facilities, which in turn hinders participation in physical activity (WHO, n. d.). Physical inactivity is one of the main risk factors for major noncommunicable diseases, causing about 10% of the burden of disease from breast cancer, 10% of colon cancers, 6% of coronary heart disease, and 7% of type 2 diabetes, thus increasing the premature mortality rate by 9% (I.-M. Lee et al., 2012; WHO, 2018). Those factors also correlate with a substantial global economic burden, contributing to $53.8 billion in health care costs, $13.7 billion in productivity losses, and $13.4 million disability-adjusted life-years for a year (Ding et al., 2016). Five hundred thousand deaths are estimated to be preventable annually if participation in physical activity increases by 10% (I.-M. Lee et al., 2012). Research has also shown that physical activity improves mental well-being (e.g., Ho et al., 2017; Ho, Louie, Chow, Wong, & Ip, 2015).

The use of virtual and augmented reality technology has been recently considered as a new approach to promoting physical activity and health behavior (Ahn & Fox, 2017). While exercise activities could be affected by environmental factors such as weather, light, and traffic (Salmon, Owen, Crawford, Bauman, & Sallis, 2003), virtual and augmented reality technology with exercise as the innovative intervention may counteract the negative environmental influences on physical activity and enhance the motivation to exercise (Plante, Aldridge, Su, et al., 2003). Reese and Nass (1996) suggest that our human brain is not fully evolved in our responses to mediated representations, thus limiting the capability to distinguish between real and virtual stimuli. Both VR and AR technologies can supplement physical intervention to

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change human behaviors.

Virtuality can be conceptualized as a continuum, along which real life setting with real objects is situated on the left end side and virtual environment composed by virtual objects is on the right end side. Virtual reality is therefore an environment where is close to the right end and argument reality is close to the left end (Milgram & Kishino, 1994). Virtual reality (VR) is a digital environment in which individuals are situated in virtual surroundings and represented by virtual selves who can interact with other virtual objects beyond a physical boundary; in addition, the VR system allows the activities of participants to be tracked. There have been two common types of VR-enhanced exercise. The first one is virtual reality biking that individuals can experience biking in a non-immersive virtual environment shown on the computer screen. In about decades ago, players were required to hold the mouse button to steer a bike and change its speed (e.g., Plante et al., 2003; Plante, Aldridge, Bogden, & Hanelin, 2003). Recently VR exercise bike is equipped with integrated sensors that synchronize with a computer. Players wear a lightweight head-mounted display (HMD) and control their actions by steering their game characters (e.g., Zeng, Pope, & Gao, 2017). The HMD allows players to experience a fully immersive virtual environment.

Another one is the balance exercise program such as Xbox 360 and Nintendo. The motion capture sensor, installed on top of the display monitor, captures body segments of a player and tracked the player's movement. The motion capture sensor camera thus transmits the player's posture into on-screen actions without a controller. Players can see their avatar and the immersed avatar on the monitor screen simultaneously following the movements of the players. This non-immersive system does not require a controller (e.g., Kim, Son, Ko, & Yoon, 2013). Recently balance exercise programs have utilized immersive VR technologies such as Oculus Rift, HTC Vive, and PlayStation VR as the display method to provide users more immersive experiences.

Augmented reality (AR) mixes real and virtual environments by establishing a user-centered world through devices such as a smartphone camera or motion tracker. It also provides reality and additional information through a wearable HMD. The AR exercise program instructs users to wear a HMD and follow the movement of a virtual target displayed in the HMD. The program can sense the user's movement and send the signal to the HMD in order to adjust the movement or repeat the task, and thus move to the next level if the user's movements are correct (e.g., Yoo, Chung, & Lee, 2013).

Social cognitive theory (Bandura, 2001, 2002) can explain the effectiveness of VR- and AR-enhanced exercise programme on physical activity and performance (Ahn et al., 2017; Fox & Bailenson, 2009). The theory states that individuals can learn behavior by observing others' behavior. Two mechanisms suggested by the theory can be applied to explain the impact of VR/AR-exercising. The first is vicarious reinforcement that individuals can observe and learn another one's behavior and model the one's behavior without rewards or punishments. The vicarious reinforcement of a model provided on the computer or television screen or inside the VR/AR HMD can motivate exercising. The second one is identification that an individual is more likely to learn the behavioral consequence of a model (including virtual model) successfully if the model is similar to that person. A study showed that individuals who viewed their virtual self exercising in the virtual environment exercised more than those viewed virtual other (Fox & Bailenson, 2009).

Effectiveness studies comparing VR-enhanced exercise and traditional exercise equipment (i.e. a stationary bike or treadmill) have been conducted to test three categories of outcome: physical activity (frequency, intensity, and duration), psychological outcome (calmness, energy, enjoyment, tension, and tiredness), and physical performance (balance, gait, and strength). In the first category, research has shown that individuals attended VR biking sessions more frequently than non-VR stationary biking sessions (Annesi & Mazas, 1997; Warburton et al., 2007), exercised longer distances (miles), exerted more power (watts), and reported higher heart rates in the VR exercise group than in the non-VR group (Murray, Neumann, Moffitt, & Thomas, 2016). Second, psychological outcomes were also examined as an outcome measure of VR-enhanced exercise effectiveness. For example, participants' enjoyment levels were higher and ratings of perceived exertion were lower in the VR-based experimental group than in the control group (Murray et al., 2016; Zeng et al., 2017). Third, previous systematic reviews have investigated exercise-based VR technology in improving balance (Booth, Masud, Connell, & Bath-Hextall, 2014; Corbetta, Imeri, & Gatti, 2015; de Rooij, van de Port, & Meijer, 2016; Donath, Rössler, & Faude, 2016; Howard, 2017; Iruthayarajah, McIntyre, Cotoi, Macaluso, & Teasell, 2017; Z. Li, Han, Sheng, & Ma, 2016), gait (de Rooij et al., 2016; Howard, 2017), and strength (Howard, 2017). AR technology, which strengthens the effectiveness of exercising by providing additional information in the real-world environment, was applied to the Otago Exercise Program consisting of walking, balance training, and muscle strengthening (e.g., J. Lee, Yoo, & Lee, 2017; Yoo et al., 2013).

Previous meta-analyses and systematic reviews have focused on the use of VR interventions in clinical settings. They have been conducted to evaluate the use of VR as a new approach to rehabilitation, compared with standard or no rehabilitation, to improve patients' physical performance after stroke (Corbetta et al., 2015; de Rooij et al., 2016; Iruthayarajah et al., 2017; Z. Li et al., 2016), and impaired balance (Booth et al., 2014). However, to the best of our knowledge, no systematic review and meta-analysis has examined the effectiveness of exercise-based VR training in improving the psychological and behavioral outcomes of physical activity among healthy individuals. Also, we were not aware of any meta-analysis investigating the effect of AR training on exercising.

Physical inactivity has been one of the strongest modifiable risk factors for morbidity and mortality, including diabetes, cancer, and cardiovascular diseases (Kohl et al., 2012; WHO, 2018). It was estimated to cause 9% of all premature deaths worldwide (I.-M. Lee et al., 2012). However, previous interventions in promoting physical activity have achieved mixed results. VR- and AR-enhanced exercise, a new form of engaging context, may serve to promote physical activity more effectively and thus prevent noncommunicable diseases in the population. The purpose of this study was to examine the effectiveness of VR-enhanced exercise on a wider range of outcomes that involve increased physical activity, improved psychological outcome, and physical performance in a healthy population, when compared with traditional and no-exercise programs (e.g., only written or video advice materials were provided).

Previous findings of the meta-analyses of VR training on physical performance in a clinical setting were mixed. Some found that VR training elicited greater benefits than did traditional training (e.g., Corbetta et al., 2015; de Rooij et al., 2016; Z. Li et al., 2016); others showed that VR interventions may not be effective (e.g., Booth et al., 2014; Iruthayarajah et al., 2017). Thus, we attempted to conduct moderation analyses to shed light on the inconsistent results. While none of the meta-analyses of the impact of VR exercise training on physical activity and performance conducted moderation analysis, no prior assumption was made to indicate the directions of the moderating effects. Therefore, we adopted an exploratory approach to testing a list of plausible moderators that are commonly examined in VR-training meta-analyses involving other outcome measures, including year of publication, participant gender and age, and exposure duration (number of weeks, sessions, and minutes). For example, a VR intervention meta-analysis studied the moderating effects for participants' characteristics (i.e., age and gender) and year of publication on anxiety (Ling, Nefs, Morina, Heynderickx, & Brinkman, 2014). A VR intervention meta-analysis found moderating effects for age on depression and reported that VR games were more effective for older adults (J. Li, Theng, & Foo, 2016). Exposure duration, frequency of sessions, and time of exposure, were also commonly included moderators in VR intervention meta-analyses (e.g., Cardoş, David, & David, 2017; J. Li et al., 2016; Parsons & Rizzo, 2008).

With the advent of technology, immersive virtual environment technology (IVET) has been developed recently to promote health (Ahn et al., 2017). In addition to traditional interactive equipment, users wear lightweight head-mounted displays to imitate multiple levels of sensory information to help them to feel, see, and hear as if they were in a real environment (e.g., Bailenson et al., 2008). We also examined immersive VR (immersive vs. not immersive) and type of reality (VR vs. AR) as the potentially exploratory moderators. Although the above moderators have been studied in other VR training meta-analyses, we did not have a specific reason to make a prediction of their influence on physical activity, psychological outcome, and physical performance.

2. Method

2.1. Literature search

We followed the PRISMA guideline to conduct the systematic review and meta-analytic study (Moher, Liberati, Tetzlaff, & Altman, 2009). All available literature, including unpublished studies, theses, and conference papers, was retrieved from the PsycInfo, ISI Web of Science, PubMed, and Google Scholar databases until March 20, 2018. We used Google Scholar to retrieve all the available literature including unpublished studies, theses, conference proceedings, and journal articles. ISI Web of Science was adopted to retrieve journal articles and conference proceedings in the Social Science Citation Index. PsycInfo and PubMed were also included because of the topic, i.e., effects of VR/AR technologies on physical and psychological outcomes, can also be studied by medical scientists and psychologists.

We adopted the following search terms used in previous meta-analyses (Cardoş et al., 2017; Donath et al., 2016): "virtual reality" or "immersive virtual environment technology" or "augmented reality" or "mixed reality" or "hybrid reality" or "augmented virtuality," in combination with "exercise" or "exercises" or "exercising" or "physical fitness" or "physical activity" or "physical activities" or "exergame" or "exergames" or "exergaming."

2.2. Selection of studies

Studies meeting the following criteria were included: (a) used exercise-based virtual or augmented reality training as an independent variable; (b) used physical activity, exercise, or performance as a dependent variable; (c) recruited healthy participants in a nonclinical setting; (d) was published as an original empirical research paper; (e) included randomized controlled trials (RCTs) in the research design; and (f) was written in English. As we aimed to examine the effectiveness of VR-enhanced exercise on exercising compared with non-VR-based exercise settings (or no exercise at all, such as watching an exercise video), we excluded those studies whose control groups involving VR technology stimulus.

Initially, the search results led to 2,188 potentially relevant studies. After removing 588 duplicates, title scanning further reduced the size to 1,600 studies. Unlike articles in other fields such as humanities, titles of experimental study normally reflect the research scope, type of participants, and key variables (both manipulated independent variables and assessed dependent variables) unequivocally. Thus, a screening of effective titles should allow us to exclude irrelevant studies. Also, if the coders were unsure about whether a study should be included or excluded, they kept those studies to the next step of abstract scanning. The abstract scanning was more effective to identify unrelated studies because a typical abstract should cover the study purposes, key variables, methods used, and the main findings. Subsequently, 548 abstracts were further scanned, and in turn 56 studies were included for detailed eligibility assessment. In the end, 22 studies were included (see Fig. 1).

2.3. Experimental group

Studies that utilized exercise-based virtual and augmented reality training were eligible for inclusion in the current meta-analysis. At least two common types of VR-enhanced exercise were examined in the literature. First, many studies used the Xbox 360 and Nintendo Wii Fit balance exercise programs as the stimulus (e.g., Jung, Ryu, & Kim, 2016; Kim et al., 2013). Participants used wireless controllers to interact with the avatars in the virtual environment shown on the television screen through the virtual reality motion-detection system (e.g., Wii board balance system). The screen displayed movements of the avatar simulating the body movement of the participant. The second most often used VR-enhanced exercise was virtual reality biking (e.g., Annesi & Mazas, 1997; Plante et al., 2003; Plante, Aldridge, Bogden, & Hanelin, 2003). Participants were asked to play a VR biking video game in which they experienced various situations such as snowing and mountain biking while cycling in virtual environments. Information including caloric expenditure, distance, heart rate, speed, and time was recorded during the game. Others included VR video game dancing, VR with walking on the laboratory treadmill, and interactive exergames. No evidence suggested the randomization was compromised or baseline imbalance in any studies. As a result, there should not be concomitant variables to bias the estimates.

2.4. Control group

Participants in the control group were commonly told to ride a traditional stationary bike, walk on a treadmill, follow their own habitual exercise routines, do warm-up and cool-down exercises, walk outdoors, and watch biking or other exercising videos.

2.5. Measures

An eligible study included three measurements: (1) physical activity, (2) psychological outcome, or (3) physical performance. In the first category, self-reported daily physical activity measures assessed the frequency, duration, and intensity of exercising. Frequency measures recorded the number of sessions participants attended. Duration measures recorded the length of time (e.g., minutes). Intensity measures recorded distance, speed, and energy expended. The psychological outcome measures commonly asked participants to report their momentary mood states including calmness, energy, tension (reversely coded), and tiredness (reversely coded) on a 4-point scale ranging from strongly disagree to strongly agree. The physical performance measures commonly recorded participants' standing, sitting and walking balance, gait, and muscle strength. Appendix 1 shows a list of the criterion measures used in the current meta-analysis.

2.6. Moderators

We analyzed the role of moderating variables in terms of the magnitude of effects on the three measures separately. The first and second authors independently coded year of publication; percentage of females; mean age; intervention duration; number of sessions; and minutes per session for the three measures. Coders also assigned values for immersive technology for physical activity and psychological outcome, and types of reality (VR vs. AR) for physical performance. Studies that did not report any of the moderators were excluded in the meta-regression analyses. Two raters independently coded these moderators for all the studies. Krippendorff's alphas ranged from 0.83 to 1.00, indicating very high to perfect inter-coder reliability. Disagreements were finally resolved.

In total, 22 research articles that included 1184 participants met the inclusion criteria. Appendix 2 summarizes the included studies along with various characteristics (i.e., moderators) in the present meta-analysis. Appendix 3 displays the sample size, category of experimental

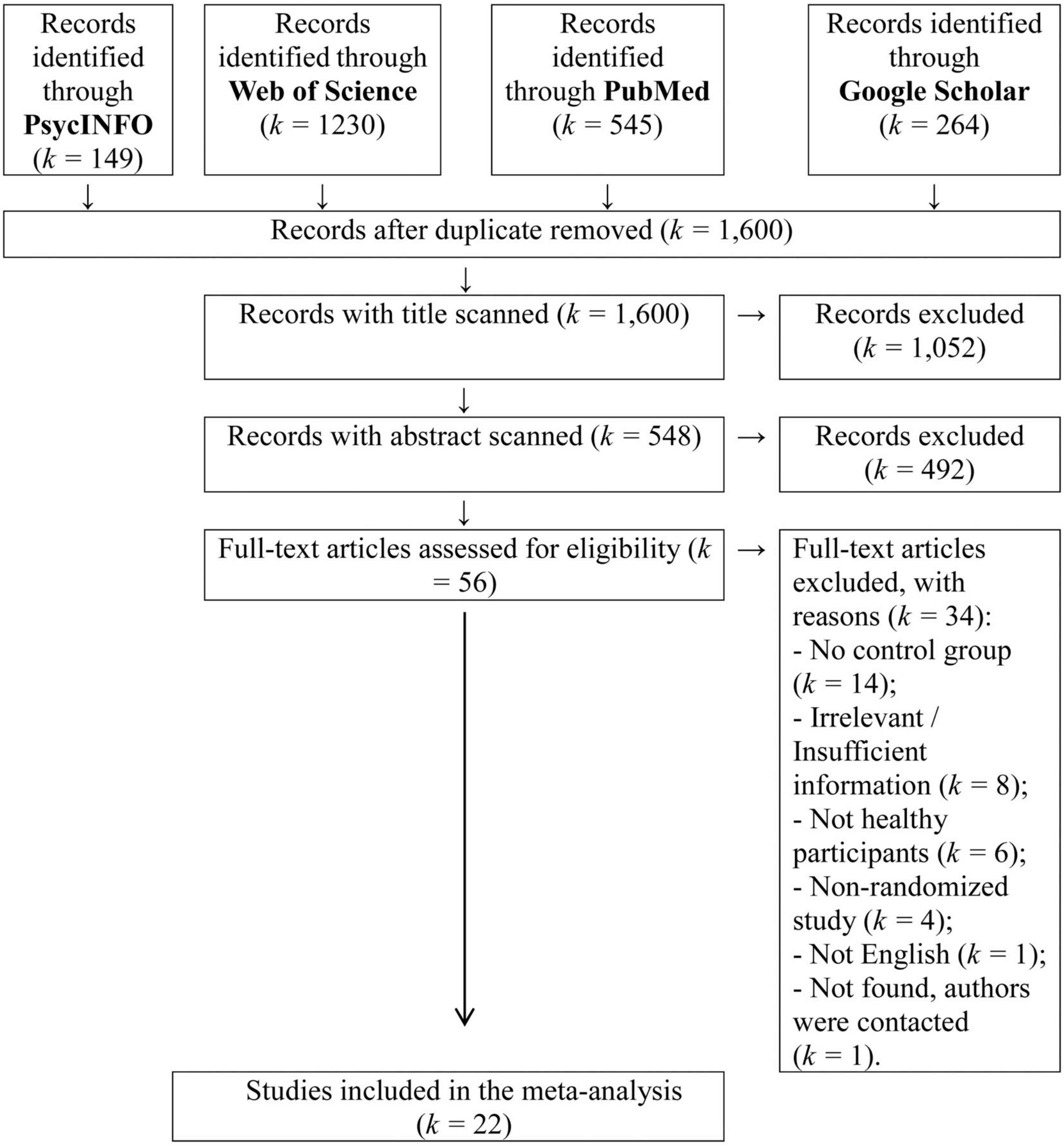


Fig. 1. PRISMA flow diagram.

and control groups, and effect sizes for both posttest and pretest-posttest-control in each individual study.

2.7. Computation of effect sizes

We used Hedge's *g* as the posttest effect size estimate. We used *g* because all the included studies are randomized controlled trials that measured differences between experimental groups and control groups in posttest continuous outcome measures. We were able to generate *g* as these studies provided sufficient information including means, standard deviations, and sample sizes of each group. We first computed posttest Cohen's $d = (M_e - M_c)/s_{pool}$, then converted *d* to *g* with the correction for small sample bias: $d\ {}^{*}\{1 - [3/(4N\text{–}9)]\}$ (Borenstein, Hedges, Higgins, & Rothstein, 2009). An effect size of *g* between 0.2 and 0.5 represents a small effect, 0.5 and 0.8 means a medium effect, and 0.8 or larger indicates a large effect size (Cohen, 1992).

As 86% (*n* = 19) of the included studies adopted the pretest-posttest-control (PPC) design, we also reported effect size for the PPC design as a sensitivity analysis. Following Morris's (2008) recommendations, an effect size based on the pooled pretest standard deviation is the best estimation: $g_{ppc} = [(M_{post,\,e} - M_{pre,\,e}) - (M_{post,\,c} - M_{pre,\,c})]/s_{pre,\,pool}\ {}^{*}\{1 - [3/(4N\text{–}9)]\}$, as it offers an unbiased estimate of the population effect size. Also, it contains a known sampling variance that is smaller than the sampling variance of effect size using separate estimates of the pretest standard deviation in the experimental and control groups. Effect sizes were calculated with the formulas in Excel.

2.8. Data analysis

Meta-regression analyses were conducted with JASP (2018, Version 0.8.5). We adopted Hedges random-effects weighted linear regressions for all analyses. The random effects model presumes that effect sizes are different from population means by both study-level variability and participant-level sampling error (Borenstein et al., 2009). For studies that reported multiple effect sizes for one outcome measure, we averaged the effect size and variance within a study (i.e., setting the correlation at 1.00), as the correlations among outcomes were unknown. We adopted this approach because a correlation of 1 shows a conservative estimation of coefficients (Hedges, Tipton, & Johnson, 2010). For studies that reported multiple effect sizes for multiple outcome measures, a shifting unit of analysis approach was used (Cooper, 1989). This approach keeps almost all the data without violating the independence assumption. For example, if a study had dependent variables of both psychological outcome and physical performance, two effect sizes were reported. If a study included one experimental group (Group $_{\text{experimental}}$) and two control groups (Group $_{\text{control}}$), two effect sizes (Group $_{\text{experimental}}$ vs. Group $_{\text{control1}}$ and Group $_{\text{experimental}}$ vs. Group $_{\text{control2}}$) were reported.

To estimate the degree of heterogeneity (i.e., variation in effect size between included studies), we presented Q and I^2 values. The Q value is the weighted sum of squared variation between the observed and the weighted average effect, determining whether or not the amount of total variance is larger than the expected value based on within-study error (Borenstein et al., 2009). I^2 value represents the proportion of observed variance that shows the real differences in effect size between studies (Borenstein et al., 2009). Low I^2 value indicates low heterogeneity. We conducted moderation analysis even if I^2 values were low in order to provide detailed results. As the results of meta-regression for categorical moderators were not significant, we did not conduct further meta-analytic analysis of variance and subgroup analysis. We conducted moderation analysis if there were 6 or more studies for a continuous study-level variable, and 4 or more studies per subgroup for a categorical subgroup variable (Fu et al., 2011; The Cochrane Collaboration, 2011).

3. Results

3.1. Physical activity

Fig. 2 displays the forest plot showing the effect sizes and the 95% confidence intervals of the studies on physical activity at posttest. We found a large effect of VR-enhanced exercise on physical activity, $k_{\text{posttest}} = 5$, $g_{\text{posttest}} = .83$, $SE = 0.18$, $z = 4.55$, $p < .001$, 95% CI = 0.47, 1.19, $Q = 20.71$, $I^2 = 0.00$. Only one study investigated duration ($g_{\text{posttest}} = .95$, $SE = 0.07$) and intensity ($g_{\text{posttest}} = .85$, $SE = 0.12$) respectively, so we were unable to conduct meta-analysis. For frequency, the results indicated a medium effect size, $g_{\text{posttest}} = .60$ (see Table 1).

3.2. Psychological outcome

We categorized the VR-enhanced exercise stimulus into two groups: VR bike and others. No effect size difference was found from posttest and pretest-posttest-control (PPC), so we collapsed the two types of VR-enhanced exercise stimulus for further analyses. We did not separate control groups with exercise (e.g., stationary bike and treadmill) and non-exercise (i.e., watching exercise video), as no type of control group difference was found at posttest and PPC. The forest plot shows the effect sizes and the 95% confidence intervals of the studies on psychological outcome at posttest (primary analysis) and at PPC (sensitivity analysis) in Fig. 3. The results demonstrated no significant effect at posttest, $k_{\text{posttest}} = 10$, $g_{\text{posttest}} = .01$, $SE = 0.11$, $z = 0.07$, $p = .94$, 95% CI = −0.21, 0.23, $Q = 0.01$, $I^2 = 0.00$; and at PPC, $k_{\text{ppc}} = 8$, $g_{\text{ppc}} = .08$, $SE = 0.12$, $z = 0.70$, $p = .49$, 95% CI = −0.15, 0.31, $Q = 0.49$, $I^2 = 0.00$. We found no significant effect for calmness, energy, enjoyment, tension, and tiredness at posttest and PPC (see Table 1). The results of simple meta-regressions revealed that all the moderators were not significant (see Table 2).

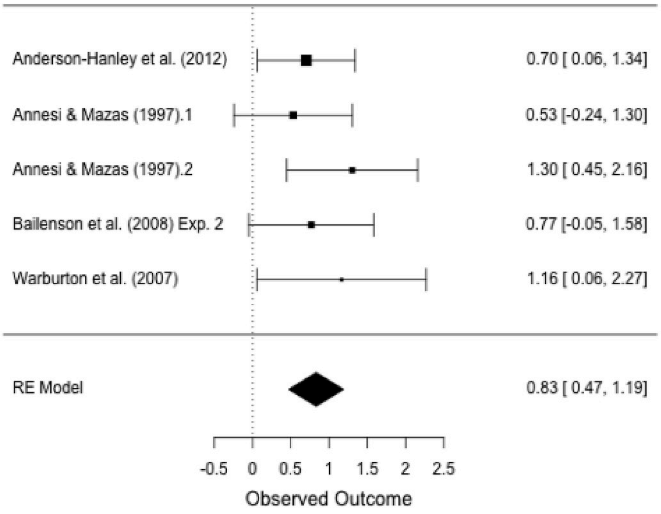


Fig. 2. Forest plot showing effect sizes (Hedges' g) and 95% confidence intervals (CIs) of studies from posttest on physical activity.

3.3. Physical performance

We identified three categories of VR-enhanced exercise: VR bike, Wii or Xbox, and others. We combined the three experimental categories because no differences were found at posttest and PPC. The two control groups (exercise group [e.g., treadmill and balance exercise] and non-exercise group [e.g., following own daily routines and attending lectures]) were not significantly different, so we combined the two types of control group. No significant AR and VR stimulus difference was found. Fig. 4 reveals the forest plot demonstrating effect sizes and 95% confidence intervals of studies on physical performance at posttest and PPC separately. We found a small effect size at posttest, $k_{\text{posttest}} = 17$, $g_{\text{posttest}} = .31$, $SE = 0.09$, $z = 3.38$, $p < .001$, 95% CI = 0.13, 0.49, $Q = 11.40$, $I^2 = 18.38$; and at PPC, $k_{\text{ppc}} = 17$, $g_{\text{ppc}} = .31$, $SE = 0.09$, $z = 3.43$, $p < .001$, 95% CI = 0.13, 0.49, $Q = 11.78$, $I^2 = 22.75$.

We found a medium effect of VR- (and AR-) enhanced exercise on strength, $g_{\text{posttest}} = .59$, $g_{\text{PPC}} = .59$; and a small effect on combined performance (i.e., balance, gait, mobility, and others), $g_{\text{posttest}} = .28$, $g_{\text{PPC}} = .30$. The results showed a small effect size for balance at posttest, $g_{\text{posttest}} = .24$; but a very small effect size at PPC, $g_{\text{PPC}} = .11$. Gait did not depend on exercise-based virtual and augmented reality training (see Table 1).

The results of simple meta-regressions demonstrated that number of weeks of exposure moderated effect size at posttest, $b_{\text{posttest}} = -0.03$, $p = .04$, 95% CI = −0.06, −0.001. The longer the exposure week, the lower the effect on physical performance. However, we did not find the same moderation effect at PPC. Number of exposure sessions also moderated effect size at posttest, $b_{\text{posttest}} = -0.01$, $p = .03$, 95% CI = −0.02, −0.001. The longer the exposure session, the lower the effect at posttest. However, we also did not find the same moderation effect at PPC (see Table 3). We did not find other moderation effects.

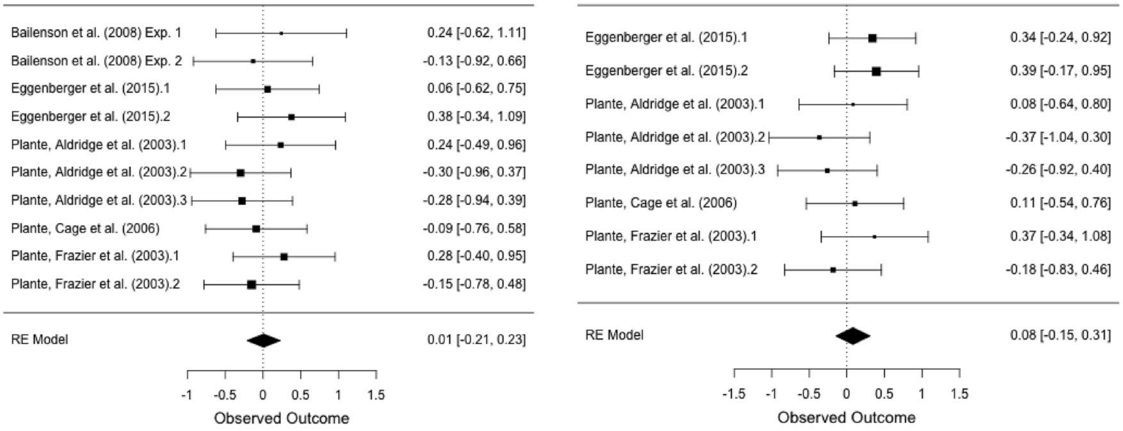
3.4. Publication bias

Publication bias was examined with Egger's test (Egger, Smith, Schneider, & Minder, 1997), Kendall's Tau rank test (Begg & Mazumdar, 1994), and a test of funnel plots. Asymmetry of funnel plot reflects evidence of publication bias. Results of Egger's test and rank test for the three outcome measures are shown in Table 4. Figs. 5–7 displays the funnel plots for publication bias assessment. Studies (dots in the funnel plots) testing posttest on physical activity (Fig. 5) and posttest and PPC on psychological outcome (Fig. 6a and b) were all located inside the boundary of the diagonal lines representing 95% confidence limit. For posttest on physical performance, one study was located outside the 95% confidence limit and three were close to the limit (Fig. 7a); for PPC on physical performance, two were outside the 95% confidence limit and two were close to the limit. Both tests investigated the interdependence of variance, effect size, and sample size among the studies. The funnel plots were visually symmetric, and all the Egger and rank tests were statistically non-significant, suggesting no evidence for publication bias.

Table 1
Meta-analyses results by physical activity, psychological outcome, and physical performance.

Outcomes	*k*	*g*	*SE*	*z*	*p*	95%CI	*Q*	I^2
Physical activity								
Frequency								
Posttest	5	0.60	0.34	1.78	0.08	[-0.06; 1.27]	3.17	95.96
Psychological outcome								
Calmness								
Posttest	6	−0.07	0.18	−0.38	0.70	[-0.42; 0.28]	0.15	87.63
PPC	6	−0.17	0.28	−0.59	0.55	[-0.71; 0.38]	0.35	96.94
Energy								
Posttest	6	0.10	0.32	0.31	0.75	[-0.52; 0.72]	0.10	97.71
PPC	6	0.01	0.49	0.01	0.99	[-0.96; 0.97]	0.00	98.97
Enjoyment								
Posttest	4	−0.17	0.31	−0.54	0.59	[-0.78; 0.44]	0.30	93.91
Tension								
Posttest	6	−0.16	0.25	−0.66	0.51	[-0.65; 0.33]	0.43	96.35
PPC	6	−0.22	0.17	−1.26	0.21	[-0.55; 0.12]	1.59	91.15
Tiredness								
Posttest	8	0.14	0.30	0.47	0.64	[-0.45; 0.73]	0.22	98.02
PPC	8	0.11	0.21	0.50	0.61	[-0.31; 0.53]	0.25	96.95
Physical performance								
Balance								
Posttest	11	0.24	0.09	2.58	0.01	[0.06; 0.43]	6.67	89.13
PPC	11	0.11	0.12	0.90	0.37	[-0.13; 0.35]	0.80	95.13
Gait								
Posttest	4	−0.08	0.09	−0.93	0.35	[-0.25; 0.09]	0.87	42.21
PPC	4	0.02	0.13	0.17	0.87	[-0.24; 0.28]	0.03	83.61
Strength								
Posttest	7	0.59	0.23	2.54	0.01	[0.13; 1.04]	6.46	95.48
PPC	7	0.59	0.19	3.14	0.00	[0.22; 0.96]	9.87	94.56
Combined								
Posttest	6	0.28	0.13	2.12	0.03	[0.02; 0.54]	4.50	92.29
PPC	6	0.30	0.15	1.97	0.05	[0.002; 0.59]	3.89	95.89

Note. Models are Hedges random-effects weighted linear regressions. *k* = number of studies; *g* = Hedge's *g*; PPC = Pretest-Posttest-Control.



A B

Fig. 3. Forest plot showing effect sizes (Hedges' g) and 95% confidence intervals (CIs) of studies from (A) posttest and (B) pretest-posttest-control on psychological outcome.

4. Discussion

The aim of this meta-analysis was to examine the effectiveness of VR- and AR-enhanced exercise, compared with traditional and no-exercise programs, in enhancing physical activity, psychological outcomes, and physical performance in healthy individuals. To the best of our knowledge, this is the first meta-analysis investigating the effect of exercise-based VR and AR training on healthy individuals' psychological and behavioral outcomes of physical activity and performance. The evidence revealed a large effect on physical activity, a small effect on physical performance, and no effect on psychological consequences of exercising compared with exercise or non-exercise controls.

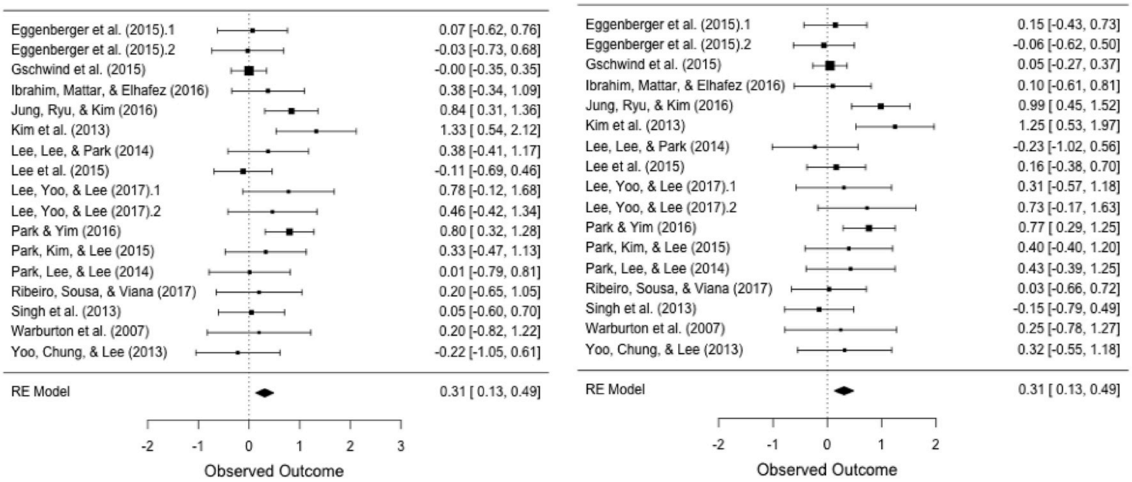
Previous VR meta-analyses have focused on the clinical effectiveness of VR interventions and rehabilitations, compared with traditional rehabilitations, in improving physical performance of patients with stroke and impaired balance (e.g., Booth et al., 2014; Corbetta et al., 2015; de Rooij et al., 2016; Iruthayarajah et al., 2017; Z. Li et al., 2016). However, from a public health perspective, as physical inactivity is one of the leading risk factors for major non-communicable diseases (WHO, 2018), we should also consider VR-based interventions as a means of primary prevention. The findings of our meta-analysis demonstrated that VR-based training has benefits in promoting physical activity and performance that surpass the benefits that traditional exercise programs may be able to produce.

In addition to reporting the posttest effect size of each study, we also provided the effect sizes for pretest-posttest-control (PPC) studies as the

Table 2
Simple Meta-Regressions for Psychological Outcome.

Predictor	*k*	*b*	*SE*	*z*	*p*	95%CI	*Q*	I^2
Group $_{\text{experimental}}$: VR bike (vs. Others)								
Posttest	10	0.14	0.24	0.58	0.57	[-0.33; 0.61]	0.33	0.00
PPC	8	−0.02	0.25	−0.06	0.95	[-0.50; 0.47]	0.004	0.00
Group $_{\text{control}}$: Other exercises (vs. No exercise)								
Posttest	10	−0.18	0.26	−0.68	0.50	[-0.69; 0.33]	0.46	0.00
PPC	8	−0.32	0.38	−0.84	0.40	[-1.07; 0.43]	0.70	0.00
Year of publication								
Posttest	10	0.02	0.02	0.92	0.36	[-0.03; 0.07]	0.85	0.00
PPC	8	0.04	0.02	1.76	0.08	[-0.004; 0.08]	3.10	0.00
% females								
Posttest	10	−0.01	0.02	−0.63	0.53	[-0.05; 0.03]	0.40	0.00
PPC	8	−0.01	0.02	−0.24	0.81	[-0.05; 0.04]	0.06	0.00
Mean age								
Posttest	7	0.003	0.01	0.54	0.59	[-0.01; 0.01]	0.29	0.00
PPC	5	0.01	0.01	1.01	0.31	[-0.005; 0.02]	1.02	0.00
Immersive								
Posttest	10	−0.26	0.23	−1.12	0.26	[-0.72, 0.20]	1.25	0.00
PPC	8	−0.51	0.27	−1.87	0.06	[-1.05, 0.03]	3.49	0.00
Follow-up exposure (vs. Post-treatment)								
Posttest	10	−0.26	0.28	−0.91	0.36	[-0.81; 0.30]	0.82	0.00
PPC	8	−0.42	0.25	−1.69	0.09	[-0.91; 0.07]	2.86	0.00
Number of exposure session								
Posttest	10	0.01	0.01	0.91	0.36	[-0.01; 0.02]	0.82	0.00
PPC	8	0.01	0.005	1.69	0.09	[-0.001; 0.02]	2.86	0.00
Session duration (minute)								
Posttest	8	0.01	0.01	1.24	0.22	[-0.01; 0.03]	1.54	0.00
PPC	8	0.01	0.01	1.85	0.07	[-0.001; 0.03]	3.41	0.00

Note. Models are Hedges random-effects weighted linear regressions. *k* = number of studies; *b* = unstandardized coefficient; PPC = Pretest-Posttest-Control.



A	B

Fig. 4. Forest plot showing effect sizes (Hedges' g) and 95% confidence intervals (CIs) of studies from (A) posttest and (B) pretest-posttest-control on physical performance.

sensitivity analysis. PPC can control for preexisting imbalance between experimental and control groups, avoiding inflated or obscured differences at posttest, allowing estimates of treatment effect when conditions are nonequivalent, and empowering each participant to be used as their own control and thus increasing statistical power (Morris, 2008; Morris & DeShon, 2002). To provide an increased precision in the estimation of the effect size of VR-based exercise on physical activity and performance, as well as the influence of its moderators, we also considered the PPC effect sizes. The PPC yielded similar effects for VR groups compared to control groups: no overall psychological outcome and a small effect on overall physical performance (This study had no pretest for studies of physical activity, so there was also a pretest sensitization problem).

The current study found that the main VR-enhanced exercise stimuli were Xbox 360 and Nintendo Wii Fit balance exercising and VR biking; others included VR video game dancing and VR walking. VR biking and others were mainly used to promote physical activity and psychological outcomes, while Xbox 360 and Wii Fit games were adopted to improve physical performance. Despite the variation, type of VR stimuli did not appear to be a significant modifying factor for the effectiveness of all the outcomes.

Consistent with a previous meta-analysis of VR rehabilitation on physical performance (Howard, 2017), our findings demonstrated a medium effect on strength and insignificant effect on gait at both posttest and PPC. In contrast, while prior VR intervention meta-analyses showed a significant effect on balance (Corbetta et al., 2015; de Rooij et al., 2016; Donath et al., 2016; Howard, 2017; Z. Li et al., 2016), the effect was only significant in the present meta-analysis using

Table 3
Simple meta-regressions for physical performance.

Predictor	*k*	*b*	*SE*	*z*	*p*	95%CI	*Q*	I^2
Group $_{\text{experimental}}$								
Posttest: VR bike (vs. Others)	17	−0.06	0.59	−0.09	0.93	[-1.21; 1.10]	0.38	31.87
Posttest: Wii or Xbox (vs. Others)	17	0.12	0.21	0.58	0.56	[-0.29; 0.53]		
PPC: VR bike (vs. Others)	17	−0.03	0.60	−0.06	0.96	[-1.21; 1.14]	0.12	37.89
PPC: Wii or Xbox (vs. Others)	17	0.07	0.21	0.33	0.74	[-0.34; 0.47]		
Group $_{\text{control}}$: Other exercises (vs. No exercise)								
Posttest	17	−0.54	0.32	−1.70	0.09	[-1.15; 0.08]	2.90	7.57
PPC	17	−0.34	0.29	−1.18	0.24	[-0.92; 0.23]	1.38	20.07
Year of publication								
Posttest	17	0.05	0.05	0.89	0.38	[-0.06; 0.15]	0.79	24.85
PPC	17	0.02	0.05	0.43	0.67	[-0.08; 0.13]	0.18	31.81
% females								
Posttest	16	−0.002	0.003	−0.52	0.60	[-0.008; 0.004]	0.27	31.47
PPC	16	−0.003	0.003	−0.92	0.36	[-0.01; .003]	0.85	23.76
Mean age								
Posttest	17	−0.003	0.004	−0.76	0.45	[-0.01; 0.01]	0.57	24.40
PPC	17	−0.001	0.004	−0.33	0.74	[-0.01; 0.007]	0.11	28.31
VR (vs. AR)								
Posttest	17	−0.003	0.30	−0.01	0.99	[-0.59, 0.58]	0.00	0.00
PPC	17	−0.15	0.30	−0.51	0.61	[-0.74, 0.44]	0.26	28.97
Number of exposure (week)								
Posttest	17	−0.03	0.01	−2.02	0.04	[-0.06; −0.001]	4.09	12.74
PPC	17	−0.02	0.01	−1.60	0.11	[-0.05; 0.005]	2.56	21.99
Number of exposure session								
Posttest	17	−0.01	0.01	−2.15	0.03	[-0.02; −0.001]	4.61	12.91
PPC	17	−0.01	0.01	−1.51	0.13	[-0.02; 0.003]	2.29	23.52
Session duration (minute)								
Posttest	17	−0.01	0.01	−0.79	0.43	[-0.02; 0.01]	0.63	24.33
PPC	17	−0.0004	0.01	−0.07	0.95	[-0.01; 0.01]	0.01	25.70

Note. Models are Hedges random-effects weighted linear regressions. *k* = number of studies; *b* = unstandardized coefficient; PPC = Pretest-Posttest-Control.

Table 4
Results of Egger's test and rank test for funnel plot asymmetry.

Variable	Egger's test	*p*	Rank test	*p*
	z		Kendall's τ	
Physical activity				
Posttest	0.93	0.35	0.60	0.23
Psychological outcome				
Posttest	0.85	0.40	0.42	0.11
Pretest-Posttest-Control	−1.11	0.27	−0.43	0.18
Physical performance				
Posttest	0.28	0.78	0.13	0.49
Pretest-Posttest-Control	0.39	0.69	0.16	0.39

posttest analysis but not in PPC analysis. One reason for the inconsistency was that the categorization of our meta-analysis was different from the previous meta-analyses. We categorized an outcome as "combined performance" that overlapped with various physical performances. For example, some VR studies used the measure Short Physical Performance Battery (Guralnik et al., 1994), which assessed both gait and balance. Thus, in this study we classified it as the combined performance. Indeed, the results demonstrated a small effect size at both posttest and PPC.

This meta-analysis is the first study to test whether the effect sizes of VR training differ across subgroups of studies of physical activity and performance. We found that all the proposed moderators, including year of publication, percentage of females, mean age, immersive or not, and exposure duration (number of weeks, sessions, and minutes) did not moderate the effect of VR training on physical activity, psychological outcomes, and physical performance. For psychological outcomes, there were indications of smaller effects among earlier published studies, having immersive components, and having longer follow-up periods. This may suggest that studies conducted more recently may have benefitted from better-designed interventions, but the effect of the VR interventions may fade significantly post-intervention. However, our moderation analysis may not be sufficiently powered because of the relative homogeneity of the studies (Hedges & Pigott, 2004). For physical performance, number of exposure weeks and sessions moderated the effect size at posttest. However, the more accurate estimation of PPC of the two covariates demonstrated no moderation effect.

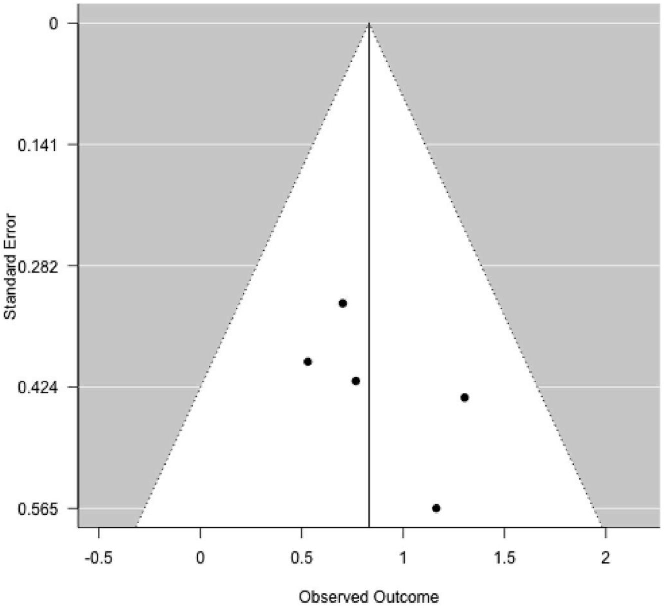


Fig. 5. Funnel plot for publication bias assessment from posttest on physical activity.

A distinctive approach of this study is to review and examine the effectiveness of both VR- and AR-assisted training. Compared with reviews of only VR or only AR training, the merit of our approach is that the influence of the telecommunication environment on exercise can be synthesized and examined within the virtuality continuum, a single

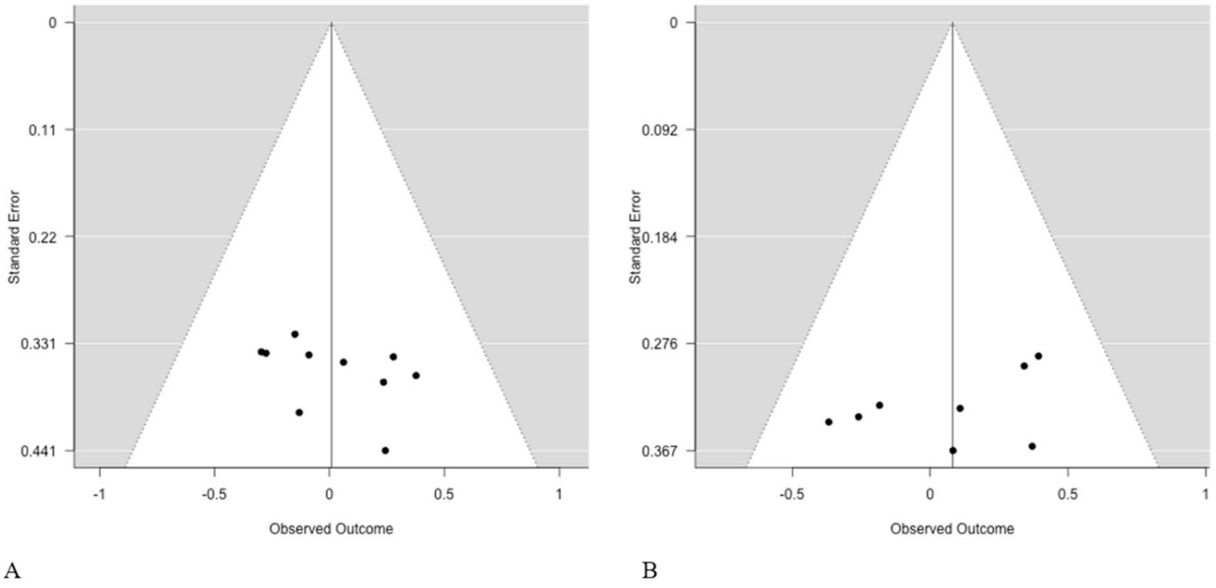


Fig. 6. Funnel plot for publication bias assessment from (A) posttest and (B) pretest-posttest-control on psychological outcome.

display connecting completely real to completely virtual environments (Milgram & Kishino, 1994). Our findings indicated that the majority of the included studies were located somewhere close to one end (VR) but less than 10% of them were on the opposite side (AR). Thus, future studies of AR-enhanced exercise should be recommended.

The results of the present meta-analysis can provide theoretical implications based on the two mechanisms suggested by the social cognitive theory (Bandura, 2001, 2002): vicarious reinforcement and identification. Our findings indicated a large effect size on physical activity but only small and no effect on physical performance and psychological outcomes respectively. Vicarious reinforcement was adopted in all the included studies that participants observed and followed the avatars in the virtual environment. However, the avatars were not created and adjusted to be similar to the participants (i.e., identification), given that following avatar designed to be similar to the self in the virtual environment was more effective in promoting exercising than using avatar that is dissimilar to the self (Fox & Bailenson, 2009). That can be one of the reasons why the effect size of exercise-based VR and AR training on physical performance and psychological outcomes were small. Future studies could test the effectiveness of VR and AR enhanced exercise providing the virtual representation of the physical self on physical performance.

Although most of the included studies in this meta-analysis and existing research in the literature rarely apply a theory-testing approach to examining the VR-exercising effects, some theoretical frameworks have been referred to understand the consequence. To convey a sense of the wider theoretical environment in which the exercising in VR/AR literature is placed, we discuss these theories accordingly. Consistent with Plante, Aldridge, Bogden, et al.'s (2003) study, theories mainly attempt to account for the physical and psychological consequences of VR-exercise programs. Our meta-analysis showed that VR training programs are effective for increasing physical activity and performance, but not psychological states (i.e., mood states). However, other theories suggest that individuals' perception of exercise can serve as a positive suggestion or perception, resulting in positive psychological consequences, as people perceive exercising as good for health. For example, the health belief model (Rosenstock, Strecher, & Becker, 1988; Shillitoe & Christie, 1989) posits that a person's self-perceived value of an activity (e.g., exercising) determines self-management and the predicted consequences of the activity (i.e., exercising). VR training program can be used as an effective self-management scheme to improve individuals' health (M. Lee, Son, Kim, & Yoon, 2015). Thus, theories of perception can be applied to explain and predict the effects of VR-exercising. Although specific theories are rarely applied to explain AR-

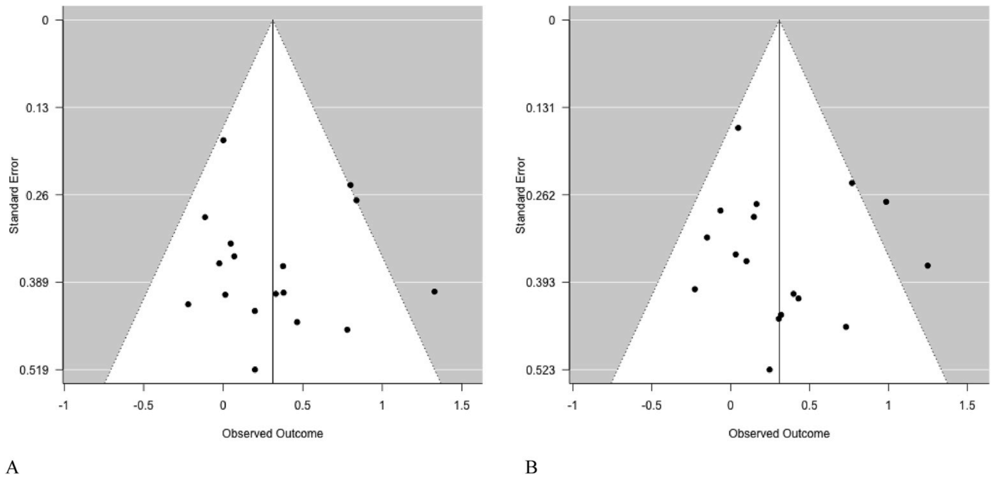


Fig. 7. Funnel plot for publication bias assessment from (A) posttest and (B) pretest-posttest-control on physical performance.

training programs, the same set of theories is also applicable to explain the AR-exercising effects.

Apart from the social cognitive theory that we discussed above, motor learning theory can also be applied to comprehend how people learn exercising via VR/AR-training program. Motor learning theory states a series of internal processes that cause permanent changes in the ability to execute certain performances as a direct outcome of experience or practice (Schmidt, Lee, Winstein, Wulf, & Zelaznik, 2019). The processes include three phases: the acquisition phase indicating the performance level; and the retention and transfer phases indicating the learning of the task. In the context of VR/AR-exercise programs aiming at promoting exercising, individuals could be trained to enhance the frequency of physical activity and strength of physical performance (acquisition), be capable to keep exercising at a later time (retention), and be able to exercise without VR and AR technologies (transfer) (e.g., Imam & Jarus, 2014). Future research could explore possible impacts and outcomes by drawing on previous results to design VR/AR-training programs.

The impact of publication bias on meta-analytic findings is one of the key methodological concerns in meta-analysis. We have evidence to substantiate the results of our meta-analysis were not biased. First, we not only included ISI Web of Science, PsycInfo, and PubMed to retrieve published journal articles (which most likely report significant results only), but also Google Scholar to identify grey literature, such as books, reports, and preprint articles. Second, the results of Egger's test and rank test were not statistically significant and the funnel plots were not visually asymmetric, suggesting no evidence for publication bias. Thus, we are confident to conclude that our findings were not affected by publication bias.

5. Limitations and future directions

The findings of this study should be interpreted with regard to the following limitations. First, no significant moderators were found despite the high heterogeneity. This made the interpretation of the summary effect size more difficult. Future studies should utilize a multi-armed factorial design to explore ways to improve intervention efficacy. Second, relatively few studies investigated the effect of VR on overall physical activity ($k = 5$). In particular, there was only one study examining the effectiveness of VR-based exercise on duration and one on intensity respectively. Thus, a meta-analysis on the two outcome measures could not be conducted. Most VR and AR studies on exercising used observational and quasi-experimental design, limiting our interpretation regarding causality. We recommend that future studies should use RCTs, the most rigorous method, to determine the effect size of VR and AR technology on physical activity, including frequency, intensity, and duration of exercising. Third, this study only covers formal publications in English-language journals. As there are emerging VR and AR studies in non-English-speaking communities and not yet published in indexed journals, we may have missed some of those studies in the current meta-analysis.

Only two AR studies were included in the present meta-analysis. In fact, recently many correlational studies on AR using survey method showed that playing Pokémon Go was positively associated with physical activity (e.g., Howe et al., 2016; Kaczmarek, Misiak, Behnke, Dziekan, & Guzik, 2017; Kogan, Hellyer, Duncan, & Schoenfeld-Tacher, 2017; Marquet, Alberico, & Hipp, 2018; Orosz, Zsila, Vallerand, & Böthe, 2018), although this positive correlation is limited to game-related physical activity and does not generalize to general physical activity (Gabbiadini, Sagioglou, & Greitemeyer, 2018).

The present meta-analysis only included three studies using immersive technology. In fact, there were studies that adopted the immersive technology to test psychological and behavioral outcomes of exercising (e.g., Zeng et al., 2017), but used non-RCTs method, so that the true causal effect cannot be guaranteed. Future immersive VR research on exercising should also take that point into consideration.

The perception of immersion (i.e., being there) is an important element that can enhance the effectiveness of VR and AR on psychological and behavioral outcomes of physical activity and performance. A meta-analysis found that higher levels of technological immersion enhanced presence—the psychological experience of “being there” (Cummings & Bailenson, 2016). We found that studies included in the current meta-analysis did not examine the degree of presence. Future studies should examine whether the level of presence moderates the effect of VR and AR training on exercising.

The transtheoretical model posits that health behavior change (e.g., exercise behavior) consists of six stages of change: pre-contemplation (no intention to take action), contemplation (intend to take action), preparation (ready to take action), action (have made obvious lifestyle changes), maintenance (working to prevent relapse), and termination (will not relapse) (Prochaska & Velicer, 1997). Our findings showed that, after controlling for the pretest, VR groups generated no effect on psychological outcome and a small effect on physical performance compared to control group. Also, our results indicated that the intervention duration (ranging from 4 to 24 weeks) did not moderate the VR-exercising link. Indeed, as the transtheoretical model predicts, previous exercise experience and interest should be measured to evaluate the changes in exercise behavior. However, we found that none of the included studies in the present meta-analysis tested previous exercise experience as a moderator or treated it as a covariate. We were not aware that the included studies examined the exercise behavior change from pre-contemplation to later stages. Future studies could investigate the effects of VR/AR technologies on exercising guided by the transtheoretical model.

6. Conclusion

While physical inactivity is known as a leading risk factor for noncommunicable diseases, VR- and AR-enhanced exercise is not only considered as a new approach for intervening patients in the clinical setting, but also promoting exercise and preventing noncommunicable diseases to the population. Previous meta-analyses have studied the use of VR interventions and rehabilitations, but none examined the effects of VR/AR-enhanced training on exercising among healthy individuals. The current meta-analysis, therefore, intended to fill this research gap. It included 22 studies of randomized controlled trials involving 1,184 healthy participants and suggested a large effect size of VR intervention on physical activity level, a small effect size on performance, and no effect on psychological outcomes. We recommend that future studies should explore the potential moderators that can further improve intervention efficacy, conduct more studies on AR-enhanced exercise training, test the effects by providing the virtual representation of the physical self, use the most rigorous method (i.e., RCTs), and investigate the effects with an immersive technology.

Acknowledgement

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.chb.2019.05.026.

Appendix 1. Measures of Physical Activity, Psychological Outcome, and Physical Performance

Outcome	Construct	Measure
Physical activity	Duration, frequency, and intensity of exercising	Aerobics Center Longitudinal Study Physical Activity Questionnaire (ACLS-PAQ; Kohl, Blair, Paffenbarger, Macera, & Kronenfeld, 1988) Attendance (number of days attended per week)
Psychological outcome	Calmness, energy, enjoyment, tension (negative), and tiredness (negative)	Activation-Deactivation Adjective Check List (AD-ACL; Thayer, 1967,1978, 1986) Perceived Exertion Scale (PES; Borg, 1982, 1985)
Physical performance	Balance, gait, and strength	6-min walk test (Crapo et al., 2002) Arm curl test (ACT; Singh et al., 2014) Berg Balance Scale (BBS; Berg, Wood-Dauphinee, & Williams, 1995) Biodex Balance System (BBS; Arnold & Schmitz, 1998) Canadian Physical Activity Fitness and Lifestyle Approach (Canadian Society for Exercise Physiology, 2010) Digital manual muscle tester (measuring muscle strength) Foot Print (measuring balance) Force plate (measuring ground reaction force N/kg) GAITRite electronic walkway system (Bilney, Morris, & Webster, 2003; van Uden & Besser, 2004; Webster, Wittwer, & Feller, 2005) Good Balance system (measuring standing and sitting balance) Multimodal dynamometer (measuring muscle strength) Senior Fitness Test (Rikli & Jones, 1999; Roberta & Jones, 2001) Short-version Physiological Profile Assessment (PPA; Lord, Menz, &Tiedemann, 2003) Surface electromyography (measuring muscle strength) Short Physical Performance Battery (SPPB; Guralnik et al., 1994) Ten Step Test (TST; Miyamoto et al., 2008) Timed Up and Go test (TUG; Podsiadlo & Richardson, 1991)

Appendix 2. Studies Included in the Meta-analysis

Study	Year	Female	Age	Immersive	Intervention duration	Session	Mins	Reality
Anderson-Hanley et al.	2012	78.48	78.76	No	12 weeks	60	45	VR
Annesi & Mazas	1997	71.79	37.71	No	14 weeks	42	25	VR
Bailenson et al. (Experiment 1)	2008	51.22	22.80	Yes	post-treatment	1	NA	VR
Bailenson et al. (Experiment 2)	2008	50.00	21.20	Yes	post-treatment	1	NA	VR
Eggenberger et al.	2015	64.79	78.90	No	24 weeks	52	60	VR
Gschwind et al.	2015	61.20	74.70	No	16 weeks	48	40	VR
Ibrahim, Mattar, & Elhafez	2016	53.33	41.75	No	4 weeks	12	15	VR
Jung, Ryu, & Kim	2016	0.00	23.47	No	4 weeks	12	30	VR
Kim et al.	2013	84.38	67.37	No	8 weeks	24	60	VR
Lee, Lee, & Park	2014	NA	19.40	No	6 weeks	18	25	VR
Lee et al.	2015	100.00	68.22	No	8 weeks	24	60	VR
Lee, Yoo, & Lee	2017	100.00	74.93	NA	12 weeks	36	60	AR
Park & Yim	2016	94.44	73.54	No	6 weeks	12	20	VR
Park, Kim, & Lee	2015	20.83	65.85	No	8 weeks	24	30	VR
Park, Lee, & Lee	2014	37.50	23.10	No	6 weeks	18	40	VR
Plante, Aldridge, Bogden et al.	2003	50.00	38.88	No	post-treatment	1	30	VR
Plante, Aldridge, Su et al.	2003	66.23	NA	Yes	post-treatment	1	20	VR
Plante, Cage et al.	2006	58.04	NA	No	post-treatment	1	20	VR
Plante, Frazier et al.	2003	59.50	18.58	No	post-treatment	1	30	VR
Ribeiro, Sousa, & Viana	2017	100.00	29.06	No	4 weeks	12	30	VR
Singh et al.	2013	100.00	62.56	No	6 weeks	12	30	VR
Warburton et al.	2007	0.00	22.50	No	6 weeks	18	30	VR
Yoo, Chung, & Lee	2013	100.00	74.34	NA	12 weeks	36	40	AR

Note. Year = Year of publication; Female = % of females; Age = Mean age; VR = Virtual reality; AR = Augmented reality.

Appendix 3. Effects Sizes for Meta-analyses: Differences in Physical Activity, Psychological Outcome, and Physical Performance Between Experimental and Control Groups

Study	*N*	Experimental group	Control group	Posttest Hedge's g			Pre-Post-Control Hedge's g		
				PA	Psy	PP	PA	Psy	PP
Anderson-Hanley et al. (2012)	79	VR bike	Stationary bike	0.70					
Annesi and Mazas (1997)	39	VR bike	Stationary bike 1	0.53					
			Stationary bike 2	1.30					
Bailenson et al. (2008) (Experiment 1)	41	Others	Others (no exercise)		0.24				
Bailenson et al. (2008) (Experiment 2)	24	Others	Others (no exercise)	0.77	−0.13				
Eggenberger, Theill, Holenstein, Schumacher, and de Bruin (2015)	71	Others	Treadmill 1		0.06	0.07		0.34	0.15

			Treadmill 2		0.38	−0.03	0.39	−0.06
Gschwind et al. (2015)	153	Others	Others (exercise)			0.00		0.05
Ibrahim, Mattar, and Elhafez (2016)	30	Wii or Xbox	Others (exercise)			0.38		0.10
Jung et al. (2016)	30	Wii or Xbox	Treadmill			0.84		0.99
Kim et al. (2013)	32	Wii or Xbox	Others (no exercise)			1.33		1.25
D. Lee, Lee, and Park (2014)	24	Wii or Xbox	Others (exercise)			0.38		−0.23
M. Lee et al. (2015)	54	Wii or Xbox	Others (exercise)			−0.11		0.16
J. Lee et al. (2017)	30	Others	Others 1 (exercise)			0.78		0.31
			Others 2 (exercise)			0.46		0.73
J.-H. Park and Yim (2016)	72	Others	Others (exercise)			0.80		0.77
E.-C. Park, Kim, and Lee (2015)	24	Wii or Xbox	Others (exercise)			0.33		0.40
J.-S. Park, Lee, and Lee (2014)	24	Wii or Xbox	Others (exercise)			0.01		0.43
Plante, Aldridge, Bogden, & Hanelin (2003)	58	VR bike	Stationary bike		0.24		0.08	
Plante, Aldridge, Su, et al. (2003)	116	Others	Others (exercise)		−0.30		−0.37	
			Treadmill		−0.28		−0.26	
Plante, Cage, Clements, and Stover (2006)	75	Others	Others (exercise)		−0.09		0.11	
Plante et al. (2003)	91	VR bike	Others (no exercise)		0.28		0.37	
			Stationary bike		−0.15		−0.18	
Ribeiro, Sousa, and Viana (2017)	44	Wii or Xbox	Others (no exercise)			0.20		0.03
Singh et al. (2013)	38	Wii or Xbox	Others (exercise)			0.05		−0.15
Warburton et al. (2007)	14	VR bike	Stationary bike	1.16		0.20		0.25
Yoo et al. (2013)	21	Others	Others (exercise)			−0.22		0.32

Note. PA = Physical activity; Psy = Psychological outcome; PP = physical performance; VR = Virtual reality.

1 Note: To provide detailed results we conducted moderation analysis even if k was low. VR-enhanced exercise stimuli were categorized into two groups: VR bike and others. As the results showed no effect size difference between the two types of experimental stimulus, we collapsed the two types of VR-enhanced exercise for subsequent analyses. We did not find an effect size difference between the control group with exercise (i.e., traditional stationary bike) and non-exercise (i.e., exercise video watching). Thus we combined the two types. The results of simple meta-regressions showed that year of publication, percentage of females, mean age, immersive VR technology, and different measures of exposure duration did not moderate effect size for physical activity (see Table S1).

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