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Published

2016

Book Title

Virtual Reality: Advances in Research and Applications

Version

Accepted Manuscript (AM)

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Neumann, D. L. (2016). On the use of virtual reality in sport and exercise: Applications and research findings. In Z Hill (Ed.), *Virtual reality: Advances in research and application* (pp. 153-182). Hauppauge NY: Nova Science Publishers Inc.

On the Use of Virtual Reality in Sport and Execise: Applications and Research Findings

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Abstract

The application of virtual reality (VR) technology in sport and physical exercise has the potential to improve sport performance, increase adherence and enjoyment of exercise, and provide competitive and non-competitive physical activity interactions among people in geographically diverse areas. There are also challenges to VR applications and these require developers to adopt an evidence-based approach in their work. Accordingly, the use of VR in sport and physical exercise is reviewed. A definition of VR in sport and exercise is proposed from the perspective of the athlete. This approach potentially broadens the ways in which VR can be applied in sport and exercise. Most applications to date have been based on endurance type activities, such as cycling, running, and rowing. In this work, various factors have been shown to influence performance, psychological, and physiological outcomes. VR has shown to improve adherence to exercise, be effective in training race pacing strategies, enhance effort, improve mood and enjoyment, and increase cognitive functioning when compared to control conditions. Elements of the virtual environment, such as the presence of real or virtual others and its immersive properties, can also have additional effects on outcomes. Furthermore, factors related to the individual, such as attentional focus and competitiveness, can influence outcomes. Thus, the use of VR in sport and exercise may be

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conceptualised as reflecting the independent and interactive effects of the sport or exercise task, the interactions with the virtual environment, and the characteristics of the individual user. Research directions and future applications for VR in sport and exercise are discussed.

Keywords: virtual reality, sport, exercise, athlete, performance

Introduction

The field of sport and exercise has traditionally been quick to embrace new technologies. Athletes and their coaches have been eager to seek ways to gain an edge through improved performance during competition and enhanced training practices. Computer-based applications have been a key driver in more recent technological developments. More powerful processors, greater storage of information, and miniaturisation have allowed for various applications that were not thought of decades ago. One such application is the use of virtual reality in sport and exercise. The present chapter aims to review research on virtual reality in sport and exercise and to describe how the technology can be used to help professional sports people, recreational athletes, and the causal exerciser.

Many of the factors that are relevant to the application of virtual reality in sport and exercise can be illustrated by considering a case example. Murray, Neumann, Moffitt, and Thomas (2016) recently examined performance, physiology, and psychological states during a virtual rowing task. Participants were women 18 to 30 years who were novice to the sport, although they were screened to be healthy and fit enough to undertake the task. The virtual rowing task consisted of rowing on an ergometer. The ergometer was interfaced with a computer and software (NethAthlon 2 XF) to display a virtual river course on a large screen. The virtual world depicted the rower from a third person perspective in which the movement of the oars mirrored the movement of the handle on the ergometer. The avatar was also configured so that it resembled the participant in appearance (female, same skin colour etc.).

In the experiment by Murray et al., (2016), the women initially completed a 9 min baseline row without any virtual environment being displayed. Following the baseline, they were asked to complete another row of 9 min duration to the best of their ability. One group was again given no exposure to the virtual river course during this second row. A second group was asked to row in the virtual environment. A third group also rowed in the virtual environment but did so in the presence of another virtual rower who was their teammate. The women were told that the virtual teammate was another person completing the row at a different location. Participants were given the opportunity to speak to them via telephone (in reality the other person was a confederate). Furthermore, the participant was told that their teammate had rowed 40% further than they did in the baseline row and that the team score would be based on the team member who rowed the shortest distance during the 9 min row. Through the use of three groups, Murray et al., (2016) were able to examine the effects of the virtual environment and the effects of a virtual teammate on outcomes.

The results reported by Murray et al., (2106) showed that rowing on the virtual river course increased the distance rowed and the average power output across the 9 min trial. Moreover, participants who rowed in the virtual environment perceived the task to be more interesting and enjoyable than those who rowed without virtual reality. The presence of another person in the virtual environment had an additional effect. The women who rowed in the presence of a teammate showed an overall higher heart rate and covered a longer distance than women who rowed alone in the virtual environment. Interestingly, all group differences emerged in the absence of any significant differences in felt arousal, perceived exertion, or negative affective states. The improved performance outcomes thus did not come at a cost of increased negative feelings.

The experiment reported by Murray et al., (2016) illustrates several features that are common to virtual reality applications in sport and exercise. The rowing task used is typical of the tendency to study endurance sports such as cycling (e.g., Anderson-Hanley, Snyder, Nimon, & Arciero, 2011), running (e.g., Nunes, Nedel, & Roesler, 2014), and walking (Baños et al., 2016). The participants recruited for the studies also tend to be young adults (typically university students) who are novice to the sport task being used. In terms of the virtual reality system, like many other researchers, Murray et al., (2016) used commercially available software that interfaced with an ergometer. Some researchers have used all-in-one systems in which the ergometer and virtual environment are an integrated system (e.g., Snyder, Anderson-Hanley, & Arciero, 2012). Also typical is displaying the virtual environment on a computer monitor or as a projected image on a screen. Using a third person perspective (e.g., Mestre, Ewald, & Maiano, 2011; Plante, Aldridge, Bogden, & Hanelin, 2003; Plante, Frazier et al., 2003) is also commonly used as is having the presence of others in the environment in at least some conditions. Finally, the study demonstrated that virtual reality can have an effect on outcomes during a sport-related task and that the outcomes observed may be further influenced by other factors operating in the study (e.g., the presence of others).

The present chapter aims to provide a narrative review on the use of virtual reality in sport and exercise. The review begins by considering the definition of virtual reality in the context of current applications in sport and exercise. It will then give an overview of the types of virtual reality systems and applications that have been used in research to date. Research that has examined the basic effects of virtual reality will be reviewed. However, it will be seen that there are many variables that may mediate or moderate the effects of virtual reality. These variables are considered in terms of how they influence performance, physiology, and psychological states. From the review, appropriate theoretical frameworks from which to study virtual reality in sport are considered. Finally, future research areas are suggested to highlight some of the key unanswered questions arising from the current research.

Defining Virtual Reality in Sport and Exercise

Baca, Dabnichki, Heller, and Kornfeind (2009) used the phrase *ubiquitous computing in sports* to describe how computer-based technologies can be used to acquire, analyse, and present information related to performance without it interfering with competition or training. The notion highlights the use of technology in a way that the athlete is not even aware of it. It also presents an ambitious goal for virtual reality applications. It could be argued that the ideal virtual sporting environment is one in which the athlete feels so completely immersed that they are focussed solely on their performance and not on the artificial nature of the task. One might expect that this ideal would come about through the use of equipment that provides complete sensory stimulation (e.g., head mounted display, stereophonic headphones), depicts the virtual environment with a high resolution and lifelike accuracy, and that virtual objects that are immediately responsive to the user. However, awareness is defined from the point of view of the user. It may be possible for less technologically dependent approaches to induce the same level of immersion if used appropriately. Such considerations also bear upon the appropriate definition for virtual reality when applied to sport and exercise.

Virtual reality as a term has been surprisingly difficult to define. The difficulty may, in part, stem from the different perspectives that may be taken. Definitions may vary according to whether they are grounded in the technology of the system or whether they take the experiential perspective of the user (Steuer, 1992). A technology-based definition could, for example, refer to the requirement of using a head mounted display (HMD) or Cave Automatic Virtual Environment (CAVE), headphones for auditory stimuli, and wearable sensors to allow for interaction. Technological-based definitions have been criticised because they lack theoretical dimensions along which there can be variations in the experience of virtual reality (Steuer, 1992). Moreover, a definition based on technology tends to be dichotomous in implying that virtual reality is present only if certain types or configurations of equipment are used. For reasons such as these, researchers have largely approached the issue of defining virtual reality from an experiential perspective (e.g., Baños et al., 2000; Sherman & Craig, 2002).

A technology-free definition would benefit sport and exercise practitioners because of the unique challenges posed by these applications. If virtual reality were to be restricted to the use of a HMD or CAVE it would not be possible to virtually engage in some sports. For example, running on a treadmill would be dangerous if the participant had their entire field of vision of the outside world obscured by a HMD. A treadmill-based task has been used in conjunction with a HMD, but it only involved walking and thus posed low risk to the participant (Plante, Aldridge et al., 2003). The review of the literature presented in this chapter revealed few researchers who have used a HMD and only two researchers who had used CAVE (Chen, Ponto, Tredinnick, & Radwin, 2015; Sigrist, Rauter, Marchal-Crespo, Riener, & Wolf, 2015). Yet, researchers consistently referred to their approach as using virtual reality. Likewise, auditory stimuli are also infrequently used or not reported in research. In some applications it would be uncomfortable for athletes to wear headphones. For a definition of virtual reality to be applicable to sport, it would be better to focus on the experience of the athlete rather than on the technology.

Sherman and Craig (2002) argued that there are four key elements of a virtual reality experience. These elements provide a useful framework to conceptualise applications in sport and exercise. The first element is that of a virtual world. The virtual world is a collection of objects that an individual can be exposed to via various mediums (e.g., computer screen, HMD, CAVE), although the medium itself does not need to be predefined. As such, virtual reality applications in sport could potentially stimulate only one sense (e.g., visual only) and could be relatively low-tech (e.g., the screen of a smartphone). The second element is immersion, which can be composed of physical and mental elements. Physical immersion, the sense of the body being partly or wholly present in a virtual environment, is of obvious importance for sport applications because of their physical nature. Mental immersion is a term that can be used interchangeably with the sense of presence (Sherman & Craig, 2002). It refers to being involved and deeply engaged. The third element is sensory feedback, which refers to the virtual reality system giving information to the user about their physical position. In a virtual sporting application, this might be their position and movements on a race track relative to virtual landmarks or relative to other athletes. The fourth element, interactivity, is related to sensory feedback. For feedback to occur, the system must be able to monitor movements and use this information to update the virtual world. This responsiveness to the actions of the user allows for interactivity. Typically, interactivity is considered at an individual level in terms of how the user can manipulate objects of the virtual world. However, the concept can also be extended to describe interactivity with others in a virtual space. This is important for sport because others may be present as observers, competitors, or teammates.

The framework of virtual reality proposed by Sherman and Craig (2002) can be used to suggest a definition of virtual reality applications in sport and exercise. Virtual reality in sport and exercise can be defined as *a situation when an athlete is engaged in a sport or exercise within a virtual world that induces a sense of mental and physical presence and enables feedback from and interaction with the virtual world*. Note that this definition takes the perspective of the user (athlete) and is intended to allow for virtual reality applications in all sports. However, it is recognised that it may be significantly more difficult to develop virtual reality applications is some sports than in others.

The proposed definition is purposefully broad by not restricting the virtual world to a computer-simulated virtual environment. As such, the definition allows for the use of video footage, such as that produced from a 360° camera, so long as it allows for feedback and interactivity. Such applications would be highly unlikely in most sports but may be possible with endurance sports such as running, rowing, and cycling where the type of interaction is relatively simple. For example, the Tacx trainer software 4 advanced version includes film clips depicting real life cycling routes. While the use of actual cycling routes has the advantage of increased realism, it may only represent virtual reality if the speed through the route is linked to the amount of effort the athlete exerts on the bicycle (i.e., it has interactivity).

The above definition includes the key elements of mental and physical presence. For this reason, it is important for researchers to measure these attributes to ensure that the approach used did indeed induce a feeling of presence. In a cycling task, it has been shown that the level of presence induced by the virtual environment influences performance outcomes (Ijsselsteijn, de Kort, Westerink, de Jager, & Bonants, 2004; Vogt, Herpers, Scherfgen, Strüder, & Schneider, 2015). Presence can be measured through self-report scales. For example, the Reality Judgement and Presence Questionnaire (Baños et al., 2000) and the Presence Questionnaire (Witmer & Singer, 1998) have been used to measure presence in a variety of virtual reality applications. However, the validity and reliability of these scales have not yet been demonstrated with virtual sport and exercise tasks.

The final aspect of the proposed definition is the requirement for feedback and interactivity. In most cases, feedback will be in the form of performance feedback such as distance travelled, shot accuracy, or points scored as relevant for the sport. Feedback need not be visual in nature. It could be auditory, tactile, or a range of other senses. Feedback is best when it is immediate and relevant. Interactivity should also be produced with minimal delay and feel natural to the athlete. These properties will also help to induce the feeling of mental and physical presence in the virtual sport environment.

Despite defining virtual reality applications in sport and exercise from the perspective of the athlete, it may be difficult to determine the boundary conditions for what constitutes virtual reality and what does not. As noted previously, allowing for the virtual world to be created in ways that do not rely on a computer-generated visual environment provides for other approaches to be used (e.g., video footage of a real world, auditory only input). However, interactivity must still be present. For example, three-dimensional (3D) and two-dimensional (2D) video training simulations have been used in sport training (see Farrow & Raab, 2007). These applications can be immersive but they lack interactivity. The mobile device applications "Zombie Run" (Six to Start and Naomi Alderman), "Ingress" (Niantic Inc.), and "Pokémon Go" (Niantic Inc.) contain elements of immersion and interactivity. Zombie Run is also unique in that it is purely auditory in nature in that participants jog or run while hearing a mission related to invading zombies. Such applications may represent augmented reality rather than virtual reality. In addition, games like Pokémon Go are clearly not sport related, although they contain elements of physical activity.

Whether the virtual environment relates to a "sport" and "exercise" in a true definitional sense is an important factor to consider. This is particularly relevant to when researchers have used commercial gaming packages and exergames (for reviews see Guy, Ratzki-Leewing, & Gwardry-Sridhar, 2011; Peng, Crouse, & Lin, 2013). Many exergames do not simulate a sport although they may require physical movements to play. One such example is Fruit Ninja Kinect 2 for the Microsoft Xbox One console system. In addition, some console system games are labelled as sports but it is debatable as to whether the game sufficiently simulates the sport. For example, the Wii Sports software will have users play "tennis" although the court and virtual players are substantially different from reality. Similarly, "running" is simulated by jogging on the spot. However, the distinction is not always clear cut. Tirp, Steingrover, Wattie, Baker, and Schorer (2015) reported a study in which the Microsoft Kinect Sport 2 software was used to teach the skill of dart throwing. The software simulates a game of darts in which the user moves their arm in the same manner as throwing a real dart. Tirp et al., (2015) showed that training in virtual dart throwing improved throwing accuracy with virtual darts and real darts more than a control condition. Moreover, the improvements in the virtual training condition were similar to that observed in participants who trained with real darts and a dart board. The results are promising in suggesting that training in a virtual environment can translate to performing the sport in the real world. However, it is noteworthy that the virtual dart game used by Tirp et al., (2015) did not actually require the relevant sporting equipment (i.e., real darts) to be used. The game thus did not simulate the weight and feel of moving and releasing a dart through the air.

The boundary conditions for what constitutes virtual reality are more easily defined for sport than they are for exercise. Virtual sports will generally require activities that have a close resemblance to the sport as experienced in real life. Sports will require physical exertion to be combined with motor skills and hand-eye co-ordination within a competitive situation (Australian Bureau of Statistics, 2008). It is also desirable that the interaction with the virtual sport occurs through the same sporting equipment rather than through modified equipment or no equipment. Exercise is a more general term. It can be distinguished from mere physical activity and even be narrowly defined with reference to exercises that are based on sports (e.g., cycling, rowing, running). However, more generally exercise refers to structured activities that involve repetitive actions that individuals engage in for the purpose of maintaining or improving their physical fitness (Australian Bureau of Statistics, 2008). The latter definition, combined with a more broad definition of virtual reality, could potentially include some elements within the training software running on game console systems (e.g., Wii Fit, Zumba Fitness, UFC Personal Trainer). However, in making this decision it is important to test whether such applications contain the key elements of virtual reality as has been described previously, namely a virtual world, immersion, sensory feedback, and interactivity (Sherman & Craig, 2002).

Virtual Reality Systems in Sport and Exercise

Virtual reality applications in sport and exercise are comprised of the sport or exercise task, the virtual reality environment and interface, and the user. The sport and exercise tasks used in research to date have largely been continuous or endurance type tasks in contrast to intermittent and skill-based tasks (e.g., golf, baseball batting). This bias may reflect the ease with which the sport may be translated into a virtual environment, the availability of commercial equipment, and the wider application of sport-related exercise. Perhaps the most commonly researched virtual sport is cycling (e.g., Anderson-Hanley et al., 2011, 2012, 2014; Annesi & Mazas, 1997; Ijsselsteijn et al., 2004; Irwin, Scorniaenchi, Kerr, Eisenmann, & Feltz, 2012; Legrand, Joly, Bertucci, Soudain-Pineau, & Marcel, 2011; Mestre et al., 2011; Oliveria et al.,2015; Plante, Aldridge et al., 2003; Plante, Frazier et al., 2003; Snyder et al., 2012; Vogt et al., 2015). There are several commercial software packages for cycling in a virtual world, including ErgVideo™, CycleOps Virtual Training, Zwift, Velo Reality, and Tacx Trainer Software 4 Advanced. Commercial virtual reality software also exists for a range of other sports, including running, rowing, golf, football, baseball, and hockey.

In addition to the virtual reality software, the virtual reality environment will incorporate a means by which the athlete can interact with the environment. For endurance sport tasks, interaction can occur by means of an exertion interface (Mueller, Stevens, Thorogood, O'Brien, & Wulf, 2007) such as a treadmill, ergometer, ski trainer, or bicycle trainer. Effort on the exertion interface (e.g., rowing with a higher stroke rate) is translated into changes in the virtual world (e.g., faster oar movements, increased speed through the water). Ergometers and treadmills can be interfaced with a computer through USB cables or through a wireless ANT+ receiver and USB dongle to transmit information such as speed, power, and cadence or stroke rate. For an optimal experience, the interface should work both ways such that the virtual world can influence the physical properties of the exertion interface. For example, travelling up a hill could cause a treadmill to increase the incline or cause a cycling trainer to increase the resistance when pedalling. The interface for skill-based sports can consist of the sporting equipment being used (or a suitable approximation of it) along with movement sensors or a video capture system. For example, the Golfzon virtual reality simulator for golf examined in the study by Lee, Chung, and Lee (2012) uses standard golf clubs, standard golf balls, a playing surface that tilts according to the fall of the virtual ground, and a vision sensor to measure the club trace, impact, and ball reactions.

As noted earlier, virtual environments are largely displayed on a computer screen or as a projected image. A larger display with multimodal components has the potential to increase the amount of presence or immersion in the virtual world during a cycling task (Vogt et al., 2105). Another important factor is whether the environment is depicted from a first person perspective or a third person perspective. A first person perspective could be more effective in increasing motivation and performance during virtual cycling (Ijsselsteijn et al., 2004).

The final element of a virtual reality sport and exercise system is the athlete. The characteristics of the athlete may interact with the sport task, virtual reality environment, and interface to determine performance and psychological outcomes. Relevant factors include the level of expertise, experience, physical conditioning, individual preferences, feelings of physical and mental immersion, and negative responses to the virtual environment. Given the potential importance of expertise and experience, it is surprising that most research conducted to date has used participants who are novice to the sport. This may also reflect the greater emphasis on exercise than on enhancing performance in this research. It could be argued that the greater novelty or unfamiliar nature of the virtual system will place an additional load on the attentional capacity of the athlete. Experienced athletes, who have developed greater automaticity in their performance, would be better in adapting to these increased attentional demands. Future research is required to examine this issue further.

Individual athletes or exercisers may vary according to their preferences in engaging in certain types of sports or even elements within a sport. For example, cyclists may prefer a virtual road environment over a virtual track or casual exercisers may prefer one type of exercise over another. Legrand et al., (2011) assigned one group of physically active participants (>120 min exercise per week) to either a virtual jogging or virtual cycling task but allowed a second group of participants to choose which of these two tasks to do. A third group completed a cycling task without any virtual input. As expected, all groups improved in positive affect at post-task when compared to pre-task assessment. Moreover, when assessments were conducted during the task, the participants who were given a choice of the task reported greater pleasure than participants who were given no choice of the virtual exercise or who did the cycling task without virtual input. In a related study, Oliveira, Deslandes, Nakamura, Viana, and Santos (2015) assigned one group of novice cyclists to a self-selected intensity and duration of a virtual cycling task and a second group to an imposed intensity and duration. No differences in physiological (heart rate, oxygen consumption) or psychological outcomes (perceived exertion, affect, arousal, enjoyment) were found to suggest that virtual reality technology may mitigate the expected negative effects of a higher and externally imposed exercise intensity.

Physical immersion and mental immersion in the virtual world are also potentially important factors related to the individual. In this respect, the level of immersion is treated as an individual difference factor that is independent of factors in the virtual reality environment (e.g., point of view, use of HMD). Immersion may be treated as a trait in which some individuals have a greater tendency to get immersed in virtual worlds than other people. It may also be influenced by state factors. For example, complete immersion may be more difficult to achieve when exercising at a high intensity level. Related to immersion is the individual difference variable of simulator sickness, which can be measured through questionnaires (e.g., Kennedy et al., 1993). While the lag between the virtual scene and the movement of the user is a major reason for simulator sickness, some individuals are more prone to sickness than others.

Other individual difference variables may be relevant when considering the response of the athlete to virtual reality sport and exercise. For example, gender differences in sport performance may translate differently in a virtual world than it does in real life. There are also gender differences in the level of experience with computerised environments, which may have links to exposure to science, technology, and mathematics domains (Reilly & Neumann, 2013; Reilly, Neumann, & Andrews, 2015, 2016) and use of technology through computer games. However, it should be recognised that the variation within a gender can often be greater than the variation between genders (Reilly & Neumann, 2013). Few researchers have considered gender as a variable in responses to virtual reality sport and exercise. In a study on the effects of virtual cycling on mood, Plante, Aldridge et al., (2003) had novice cyclists complete a cycling task alone, cycling with virtual reality, experiencing the virtual course alone, or a no activity baseline condition. Males reported higher energy in the first three conditions than in the baseline condition. Females, in contrast, reported higher energy when cycling alone or with virtual reality than when virtual reality was used on its own or in the baseline condition. In a similar study, Plante, Frazier et al., (2003) found that the difference in reported relaxation between the virtual reality condition alone and both the cycling alone and cycling with virtual reality was higher for females than for males. These results suggest that the effects of active exercise within a virtual environment on self-reported psychological states is greater for females than for males.

Effects of Virtual Reality on Sport and Exercise Outcomes

The effects of virtual reality on sport and exercise outcomes might be observed in several ways. A useful approach is to group outcomes according to whether they are performance, physiological, or psychological. Performance outcomes will be typically linked to the goal of the particular sport. Endurance or continuous sports like walking, running, rowing, cycling, and cross-country skiing will have performance outcomes linked to time (e.g., Hoffmann, Filippeschi, Ruffaldi, & Bardy, 2014), speed (e.g., Ijsselsteijn et al.,2004; Mestre et al.,2011), distance (e.g., Murray et al.,2016), power output (e.g., Hoffmann et al.,2014), or persistence (e.g., Irwin et al.,2012). In this respect, it can be important to distinguish between exertion interfaces that control speed (e.g., treadmills) and those which have the speed determined by the athlete (e.g., rowing ergometer). The former can be advantageous in research to examine the effects of virtual reality when physical effort is held constant by keeping the speed of a treadmill constant or by varying the speed to keep heart rate within a particular zone. Here, the primary focus of the research is on psychological and physiological outcomes. The latter method of using interfaces that are more directly under the control of the athlete can be advantageous in research that examines the effects of virtual reality on performance and physiological outcomes. Performance outcomes for skill-based sports will be related to the particular aims of the sport, such as points scored, goals scored, or distance. However, it is also possible to collect additional measures that may relate to the performance outcomes. For example, spatial and temporal error has been used to examine virtual rowing performance (Sigrist et al., 2015). Likewise, measures of technique and form (e.g., follow through) or physiological measures like heart rate (Neumann & Thomas, 2009, 2011) could be analysed to examine virtual golf performance.

Physiological effects of virtual reality have been examined by researchers who have access to appropriate physiological recording system or off-line analysis techniques. Measures of respiratory effort used have included O_2 consumption (e.g., Hoffmann et al., 2014; Oliviera et al., 2015), CO_2 expiration, and respiratory volume (Hoffmann et al., 2015). Heart rate (e.g., Ijsselsteijn et al., 2004; Murray et al., 2016; Oliviera et al., 2015) has been used to provide a measure of overall physiological effort and can be easily acquired using wireless technology. Many commercial virtual reality software applications will collect heart rate information from wireless fitness devices. In other applications, muscle activity as measured by electromyographic (EMG) activity (Chen et al., 2015) and electroencephalograph amplitude and frequency (Vogt et al.,2015) have been used and it may also be relevant to measure temperature, skin conductance, blood pressure, and eye blink measures (e.g., Lipp & Neumann, 2004; Lipp, Neumann, Pretorius, & McHugh, 2003; Neumann, 2002; Neumann & Lipp, 2002; Neumann, Lipp, & McHugh, 2004) to gain additional information. Off-line assessment of physiology can include measures such as blood lactate concentration (e.g., Oliviera et al., 2015). The physiological outcome measures mentioned thus far are based on measurements taken when performing the virtual sport task. Additional, post-task measures have also been taken such as body composition, strength, and brain-derived neurotropic factor (Anderson-Hanley et al., 2012). Post-task measures can be relevant when assessing the effectiveness of a virtual reality exercise program on physical and psychological health.

Psychological outcomes have been frequently measured in research on virtual reality, particularly for research that has examined exercise-based activities. A common measure is that of perceived exertion (e.g., Mestre et al.,2011; Murray et al., 2016; Plante, Aldridge et al., 2003; Plante, Frazier et al., 2003) which is typically correlated with heart rate (Borg, 1982). However, it was not correlated with heart rate during a virtual rowing task (Murray et al., 2016). Also commonly measured are variables related to affect. These measures can include enjoyment (Baños et al., 2016; Mestre et al., 2011; Oliviera et al.,2015; Plante, Aldridge et al., 2003; Plante, Frazier et al.,2003), positive and negative affect (Legrand et al., 2011; Murray et al., 2016), and mood (Plante, Frazier et al., 2003). Other psychological measures have included motivation (Anderson-Hanley et al., 2014), sense of presence (Vogt et al., 2015), and evaluations of the virtual reality system (e.g., usefulness; Sigrist et al., 2015).

Several studies have examined the effects of virtual reality in the context of an exercise program. An early study by Annesi and Mazas (1997) used a stationary cycling task with three groups of novice participants. One group used an upright stationary bicycle with no virtual reality, a second group used a recumbent stationary bicycle with no virtual reality, and a third group used the recumbent bicycle within a virtual environment. Across the 14 week program, participants in the virtual reality cycling group showed higher adherence than participants in the regular (no virtual reality) groups. However, exercise-induced feelings did not differ between the groups. In a related study, Anderson-Hanley et al., (2012) compared a stationary cycling condition with no virtual reality and a stationary cycling condition with interactive virtual tours in a group of elderly novice participants. The exercise program lasted for 3 months. The results showed that participants who cycled with virtual reality had greater executive functioning and neuroplasticity than participants who cycled without virtual reality. The results suggest that a virtual reality enhanced exercise program can reduce the risk of mild cognitive impairment during aging (cf. Anderson-Hanley et al., 2014).

Plante and colleagues (Plante, Aldridge et al., 2003; Plante, Frazier et al., 2003) conducted two studies that examined cycling in a virtual environment. The results of the first study showed that when cycling was paired with virtual reality, enjoyment was higher and tiredness was lower than for cycling with no virtual reality (Plante, Aldridge et al., 2003). In the second study, however, improvements in positive mood were more strongly related to the cycling task rather than to the use of virtual reality (Plante, Frazier et al., 2003). No differences were observed in mood between cycling with and without virtual reality when assessed immediately after a 30 minute cycling task. Virtual reality only had an effect when psychological states were assessed later in the day and only for females. The female participants who had cycled in the virtual environment reported more energy and less tiredness immediately prior to going to bed than female participants who cycled without virtual reality, who had watched a video simulating cycling, or who played with a cycling game on a computer. No differences among the conditions were found for males when assessed later in the day.

The effect of virtual reality on psychological states was also observed by Mestre et al., (2011) and Baños et al., (2016). Novice participants who cycled in a virtual reality environment reported more enjoyment than when they cycled in the absence of virtual reality in the study by Mestre et al., (2011). A tendency for a reduction in perceived exertion in the virtual reality condition was also observed. In the study by Baños et al., (2016), overweight and normal weight children reported higher enjoyment when walking in a virtual environment than when walking with no virtual reality.

As is apparent from the above studies, the majority of research examining the effects of virtual reality has been based on endurance type tasks, particularly cycling. In contrast, Chen et al., (2015) used a bicep curl exercise to examine whether the use of virtual reality could be applied to lifting weights. Novice participants completed bicep curls with differently weighted dumbbells in real life and with virtually weighted objects in a 3D or 2D virtual reality environment. The virtual reality environment was presented via a CAVE system in which motion tracking and EMG activity was used to link performance to lifting a virtual object. Lifting virtual objects was associated with higher EMG activity than lifting a real object. However, the effect of increasing the weight of different physical or virtual weights was similar for EMG activity, localised muscle fatigue, and perceived exertion ratings. The findings thus suggest that lifting virtual weights may elicit physical and psychological effects similar to that observed with lifting real weights.

As shown by the results of Plante, Frazier et al., (2003b), enhanced outcomes do not always result from using virtual reality. The effects may be restricted to certain types of outcomes or times at which the outcomes are assessed (see also Annesi & Mazas, 1997; Murray et al., 2016). Supporting the conclusion of no general effect of virtual reality, Legrand et al., (2011) asked participants to cycle or run either with or without virtual reality. An enhancement of mood was observed regardless of whether participants completed the task in a virtual environment or not, suggesting that the virtual reality component had a limited effect. In this experiment, autonomy emerged as a more important factor. Participants who were able to self-select the type of virtual task (cycling or running) reported higher positive affect than participants who were allocated a virtual task by the experimenter.

Lee et al., (2012) asked users of a virtual golf simulator to complete a survey regarding their experiences in using the system, with a particular emphasis on the role of presence and immersion. The results suggested that perceived enjoyment, perceived value, and behavioural intentions were only minimally related to feelings of presence in the virtual environment, which the authors referred to as telepresence. In contrast, the social presence, which refers to the players feeling connected together irrespective of the role played by technology, was a significant factor that influenced enjoyment, value, and intentions.

A potentially important limitation of research that has examined the effects of virtual reality in sport and exercise has been the limited number of control conditions employed in any one study. The most common control condition has been to use the same sport or exercise without virtual reality input (e.g., Anderson-Hanley et al., 2012; Annesi & Mazas, 1997; Legrand et al., 2011). In these cases, the participant does not view anything. Other control conditions used have included watching a video of the virtual environment without any interaction or physical activity (Plante, Frazier et al., 2003a) and interacting with a virtual environment but with interaction occurring through non-sport or exercise related means such as by controlling a computer mouse (Plante, Aldridge et al., 2003; Plante, Frazier et al., 2003). It may be argued that an additional control condition is needed in which there is a visual display that the participants view while completing the sport or exercise. This additional condition would control for the potential effects of directing attention to an external stimulus, which might induce a dissociative attentional focus. Furthermore, the control condition could show the same virtual environment but in a way that provides no feedback or interactivity for the participant. In this way, the condition would control for the sensory properties of the virtual environment while avoiding or reducing the sense of presence. A complete experimental design would thus be based on a 2 × 2 design with the factors of sport/exercise task (present or absent) and virtual reality (present or absent) to examine the separate and interactive effects of the sport/exercise and virtual reality.

Variables that Influence the Effects of Virtual Reality on Sport and Exercise Outcomes

The effects of engaging in sport and exercise within a virtual environment can differ according to specific variables that exist in the system. One of the factors that can have the strongest effect on outcomes is social interaction or more simply, the presence of others. As noted earlier, social presence was more strongly related to enjoyment and perceived value than was telepresence in a sample of virtual golf players (Lee et al., 2012). Others may be present in a virtual world as an avatar. Indeed, the avatar could represent a computer-controlled other, a real person who is in the virtual world at the same time, a real person who completed the same task at a previous time, or even the user themselves when they previously completed the task. Virtual reality technology thus allows for synchronous and asynchronous social and competitive interaction with others.

Theories of social facilitation and social comparison (Zajonc, 1965) may be applied to explain how behaviour in a virtual environment can change in the presence of a virtual other. The enhanced performance during a virtual rowing task when in the presence of a moderately more capable virtual other that was found by Murray et al., (2016) was explained as being due to the Köhler motivational gain effect (Kerr & Hertel, 2011). The Köhler effect occurs when an inferior team member performs better in a team or coaction situation than if they were performing individually or independently (Feltz, Kerr, & Irwin, 2011).

Irwin et al., (2012) also observed an improvement in performance when novice female participants exercised on a stationary bicycle with a more capable virtually present partner. In the task, participants were asked to continue riding at 65% of their heart rate reserve for as long as they felt comfortable. Participants persisted longer in the task when cycling with a virtually present partner in a conjunctive situation (team performance was based on who was first to stop cycling) than in a coactive situation (merely exercising independently alongside another person) and an individual condition with no virtual partner present. Moreover, these effects were observed across 5 days of testing and showed a tendency for the differences to get larger across days. Irwin et al., (2012) interpreted the improved task persistence as reflecting the Köhler motivational gain effect that is induced by a conjunctive situation. Enhanced task persistence via the Köhler motivational gain effect has also been observed in a series of studies that used an abdominal plank exercise task (Feltz, Erwin, & Kerr, 2012; Feltz, Kerr, & Erwin, 2011; Irwin, Feltz, & Kerr, 2013; Kerr, Feltz, & Irwin, 2012), although these studies did not specifically aim to use a virtual reality environment that had full interactivity.

An important aspect of interactions that can occur through virtual sports is that of competition. Competition can be created through setting up goals within the task. The effect these goals have on an individual's performance may be dependent on their levels of trait and state competitiveness. However, the results of a meta-analysis of non-virtual reality studies suggested that there is no significant overall association between competition and performance (Murayama & Elliot, 2012). Rather the effect can be inconsistent across contexts. Whether introducing elements of competition influences performance may depend on other factors, such as those outlined in social facilitation theory (Zajonc, 1965), goal-setting theory (Locke & Latham, 1985), and performance under pressure (Baumeister & Showers, 1986). In particular, individuals with high trait competitiveness will be more likely to adopt performance-approach goals and thus show enhanced performance in a competitive situation. In contrast, individuals with low trait competitiveness will adopt performance-avoidance goals and show reduced performance during competition. Thus, the use of performance-approach or performance-avoidance goals will act in different ways to mediate the relationship between competitiveness and performance (Murayama & Elliot, 2012).

The complex relationship between competition and performance has also been observed in a virtual reality environment. Anderson-Hanley et al., (2011) asked older participants to cycle in a virtual reality environment either with no virtual others being present or in competition with virtual cyclists. The introduction of competitive avatars was shown to increase cycling intensity. However, this effect was substantially larger for competitive participants (20% increase) than it was for less competitive participants (only a 6% increase). Similarly, Snyder et al., (2012) observed a relationship between participant competitiveness and performance. Using a virtual cycling task, participants competed against either a live rider (the rider was present in the same room as the participant) or a virtual rider (who the participant was informed was computer controlled). No differences between the live and virtual competitive conditions were observed for participants who were low in competitiveness. In contrast, the live competitive situation resulted in a higher power output than the virtual competitive situation for high trait competitive participants.

Nunes et al., (2014) examined motivations and performance when novice participants engaged in a virtual running task with a virtual competitor or when running in the virtual environment alone. In the competitive mode of the task, the participants had access to their own speed and heart rate as well as this information for their competitor. Moreover, different competitive modes were introduced according to whether the virtual competitor was the participant's past performance, a superior other, or another person selected by the participant. Participants reported that the competitive mode of the virtual task was more motivating and more preferred than a single player mode. Supporting these findings, performance and perceived exertion ratings were higher in the competitive mode.

In sport and exercise, another individual who can be present in the situation is a coach. In the context of virtual reality, the coach may be virtually present by being represented as an avatar in the virtual environment. Ijsselsteijn et al., (2004) showed that a virtual coach reduced perceived pressure, tension, and control during a virtual cycling task. In addition, Mestre et al., (2011) showed that enjoyment in a virtual cycling task was higher when participants followed a virtual coach pacer than when cycling in the virtual environment on their own. These findings suggest that a virtual coach may have similar positive benefits as the presence of a coach in real life. The virtual nature of the coach leads to the possibility of training athletes even when the coach is located in a different geographic location. It also suggests that artificial computer-controlled coaches may be effective, although no research has yet make direct comparisons between artificial and real-life coaches.

A different approach to that of using a virtual coach was examined by Hoffmann et al., (2014) and Sigrist et al., (2015) during rowing. A fast-start race pace strategy during rowing (i.e., start fast, slower in the middle stages, and finish with high effort) was successfully trained in a sample of novice males by Hoffmann et al., (2014). During training, participants were asked to follow the pace of an avatar that adopted the fast-start race strategy. Results showed that training with the avatar produced the appropriate race strategy speed profile and an overall faster race time performance at a post-test and subsequent retention test when compared to training in the virtual environment with no avatar. Sigrist et al., (2015) examined the role of virtual feedback in learning the skill of moving the oar in rowing. Performance improvements, as measured by spatial error and velocity error differences relative to a baseline test, were observed in groups that received virtual visual, audiovisual, and visuohaptic feedback. In addition, audiovisual feedback was more effective in improving the velocity profile than visuohaptic feedback. The studies by Hoffmann et al., (2014) and Sigrist et al., (2015) represent innovative approaches to using virtual cues and feedback to enhance sport performance.

Theoretical Approaches to Understanding Virtual Reality in Sport and Exercise

Research to date on the use of virtual reality in sport and exercise has adopted a wide variety of theoretical approaches. Some studies have been grounded in theoretical concepts related to virtual reality, for which immersion and presence are the most salient factors (e.g., Annesi & Mazas, 1997; Ijsselsteijn et al., 2004). Other studies have examined concepts that may be particularly salient in a virtual reality environment, such as motivation, attentional focus, and feedback cues (e.g., Baños et al., 2016; Mestre et al., 2011; Sigrist et al., 2015). For other studies, concepts relevant to social facilitation, competition, and autonomy have been invoked (e.g., Irwin et al., 2012; Murray et al., 2016; Nunes et al., 2014; Oliviera et al., 2015), although these tend to be more general factors that influence sport performance rather than being central to the virtual reality experience. Future research would benefit from adopting a more coherent theoretical approach to understanding virtual reality in sport and exercise.

In adopting a coherent theoretical approach, it could be useful to adapt concepts from current models in the field of sport psychology. For example, the social-cognitive perspective of perceived and sustained effort (Tenenbaum & Hutchinson, 2007), mood alteration following physical activity (Berger & Motl, 2000), attentional focus strategies during endurance (e.g., Stevinson & Biddle, 1999) and skill-based (Wulf, 2007) tasks, social facilitation of performance (e.g., Kerr & Hertel, 2011), and psychological approaches to enhancing physical activity (e.g., Hannan, Moffitt, Neumann, & Thomas, 2016) are all potentially relevant. A model of virtual reality in sport and exercise may validly draw upon these approaches based on the premise that a virtual reality environment aims to simulate a real environment. Thus, those variables that are important in the real world are likely to be important in the virtual world. For example, the effects of internal and external attentional focus during running (e.g., Neumann & Piercy, 2013) or the effects of association and dissociation attentional states during strength training (e.g., Neumann & Brown, 2013; Neumann & Heng, 2011) should translate to similar outcomes when examined in a virtual environment.

There will also be variables relevant to virtual reality that should be taken into account. As previously noted and supported by research (e.g., Ijsselsteijn et al., 2004), key among these are presence and immersion. Based on the definition of virtual reality, the role of feedback and the level of interaction are also likely to be important. Attentional focus is another factor that may play a significant role in sport and exercise with virtual reality. Baños et al., (2016) found that virtual reality decreased attentional focus on bodily sensations and increased an external attentional focus in overweight children who completed a virtual walking task. Similarly, Mestre et al., (2011) reported that virtual reality lead to an increased focus on external stimuli relative to internal stimuli. However, as noted previously, the lack of appropriate control groups in such studies limit conclusions regarding the extent that these effects are due to the virtual environment rather than an external stimulus per se.

The above considerations suggest that a theoretical approach to understanding virtual reality in sport and exercise should consist of several elements. Initially, it should be recognised that the complete system is composed of the type of sport or exercise task, the virtual reality environment, and the athlete. The sport or exercise task is important because there can be significant differences between endurance-based tasks and skill-based tasks. Given that there is less research using skill-based tasks, it is not known to what extent they should be considered separately or together. Even within the same task, there can be important differences according to the specific demands (e.g., intensity, level of challenge).

The virtual reality environment itself is another obvious element of virtual reality in sport and exercise. However, it is not necessarily the depictions of the physical environment, interactivity, or the level of immersion that are the most important. The reviewed research has shown that the presence of others, whether they are a coach, teammate, or competitor, can have important influences on performance and psychological states. In addition, virtual reality environments provide feedback on performance, particularly feedback that can be augmented (e.g., Vogt et al., 2015), which athletes can use in training. Other factors that may also be important and which require further investigation could include environment novelty and familiarity, realism, point of view, and modality.

The athlete is the user of the system and they may have important characteristics that can influence outcomes with virtual reality applications. Athlete skill level, age, level of fitness, competitiveness, and experience are all factors that can influence performance within a virtual reality environment. Factors that are more relevant to virtual reality include predispositions to feeling a sense of presence in a virtual environment, susceptibility to motion sickness, experience with virtual reality systems, and attitudes towards virtual reality training approaches. These factors require further investigation within the context of virtual reality in sport and exercise.

The sport task, virtual reality environment, and athlete will have potentially independent and interactive effects on performance, physiological, and psychological outcomes. Moreover, the outcomes may be observed at different times. Outcomes may be found during the task, such as changes in attentional focus, increased effort, or increased heart rate. Outcomes may also be found immediately following the task, such as changes in mood states. Long-term outcomes should also be considered, such as speed of recovery and adherence to an exercise program. By taking a comprehensive approach that seeks to understand the various components that make up the virtual reality system (task, virtual environment, athlete) and the outcomes (concurrent, short-term, long-term) future research may be benefited.

Future Research Directions

The use of virtual reality in sport and exercise will continue to increase in popularity in the future. The potential benefit this technology has extends across the spectrum from the occasional exercisers, those beginning a new exercise program or sport, regular exercisers and keen amateur sports people, and those who compete at the professional and elite level. The present review has highlighted benefits for performance outcomes, learning strategies, physiological and psychological perceptions of effort, and affective responses during virtual sport and exercise. Virtual applications could, potentially, lead to new and innovative approaches in the real world. For example, Hoffmann et al., (2014) showed how matching the speed of a virtual rower set to follow a race pacing strategy improved race performance on the rowing ergometer on a test trial. Implicit learning approaches such as these have potential applications in the real world. Virtual reality could be used to trial innovative training approaches in a way that simulates the real world but in a more controlled environment so as to allow greater precision or more variables to be measured than otherwise possible. Research is also needed to ensure that the effects observed when in a virtual environment will generalise to real world situations.

The changing technologies will influence the future directions that are taken with virtual reality applications in sport and exercise. Among the biggest factors include improved screen resolution for increased realism, wireless technology for ease of use, interconnectivity through the internet for social and competitive interaction, and better interfaces between sporting equipment and the virtual environment. The gaming industry is likely to be the main driving force in development. Devices such as wearable goggles that are produced for the mass gaming market will be adopted for the niche market of the semi- and full professional athlete.

A blending of technologies will also occur so that what is considered to be "virtual reality in sport" may undergo radical change. There will be a continual blending of technologies from the relatively low tech mobile phones and tablets, through to large curved ultraHD television screens driven by software running on a personal computer or console, or lightweight wearable googles connected to appropriate hardware. At the lower end there will be portability and ease of use at the cost of the feeling of presence. However, the extent to which they can still be considered as "virtual" in their application may be debated. It is possible that smartphones applications could induce a feeling of being in another place or provide real time virtual competition with another individual.

The majority of research to date has examined virtual reality during exercise and/or endurance type of sports. These include cycling, running, and rowing. Considerably less research has examined virtual reality in skill-based sports. There are increased technological challenges when creating a virtual sport environment. The most relevant of these relates to the sport equipment. Solutions are required to create an appropriate interface between the sporting equipment and the effects it exerts on the virtual environment. For example, a tennis racquet should be able to be swung at various speeds, elevations, and angles to affect the velocity, placement, and spin of a virtual tennis ball. Alternatively, the sporting equipment might be represented virtually (e.g., as a virtual dart; Tirp et al., 2015), to solve some of these problems. However, it is recommended that where possible sporting equipment is used to so that training in a virtual environment will more easily generalise to performance in the real world. Technology may also be used in the real world, such as enhanced performance feedback on accuracy (e.g., Neumann & Thomas, 2008), to help increase the similarities between the virtual and real worlds.

Another limitation of current applications and research on virtual reality is that the sports have focussed on individual performance rather than team performance. The ability to represent multiple individuals in a virtual environment has the potential to allow for groups of athletes to practice team skills and strategies. It is not surprising that such applications are less common as they require that the technological issues encountered with individual sport performance be solved in addition to technological issues associated with interfacing and representing multiple individual in the virtual space. In this respect endurance sports, particularly cycling and rowing, may be the best sports to begin research and development in team sports.

Conclusion

Advances in technology will continue to play a major role in sport and exercise at both the recreational and professional level. The application of motion sensors, smart phones, computerised modelling, networking, and wireless devices are currently and will continue to be a part of the future. These devices will also be a part of the future of virtual reality in sport and exercise. It will allow for a wider range of sports to be transposed into a virtual environment and allow for improved techniques to translate the actions of the athlete into the virtual environment. This development, along with the research to evaluate it, will benefit from adopting a coherent theoretical framework in its approach. In this way, virtual reality may be able to play an important role as part of a wider approach to improve sport performance and exercise outcomes in athletes.

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