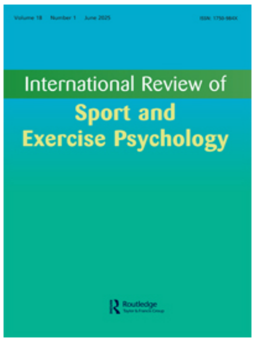

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Training decision making in sports using virtual reality: a scoping review

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ABSTRACT

There is wide interest in using technologies to enhance the training of sports-specific skills. One promising immersive technology is *virtual reality* (VR) because it can provide the athlete with rich, immersive, and representative scenarios. The key question is whether training with these systems will transfer to real-world performance. This scoping review examines the existing literature on using VR to improve sports decision-making. We identified 25 papers that used VR (which was very broadly defined by researchers) to train decision-making, and evaluated them with respect to transfer using the *Modified Perceptual Training Framework* [MPTF: Hadlow et al. (2018). Modified perceptual training in sport: A new classification framework. *Journal of Science and Medicine in Sport*, 21(9), 950–958]. In general, research is taking advantage of VR's ability to provide realistic environment, however many papers still rely on simple, non-representative actions from the athletes. Importantly, only six papers assessed transfer of training to real-world behaviour; given that transfer is the purpose of this training, this is a strong limitation on the developing evidence. The existing work does show that VR is worth investigating, so we make a series of recommendations to strengthen future research, with an emphasis on always measuring transfer and doing so guided by ecological approaches such as task dynamics [e.g. Leach, D., Kolokotroni, Z., & Wilson, A. D. (2021a). Perceptual information supports transfer of learning in coordinated rhythmic movement. *Psychological Research*, 85(3), 1167–1182; Leach, D., Kolokotroni, Z., & Wilson, A. D. (2021b). The ecological task dynamics of learning and transfer in coordinated rhythmic movement. *Frontiers in Human Neuroscience*, 506] and the MPTF.

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Introduction

Professional sports have a long-standing interest in using new technologies to try and enhance training and skill acquisition (Michalski et al., 2019; Neumann et al., 2018).

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These technologies are referred to as *modified perceptual training* (MPT; Hadlow et al., 2018). This covers a broad variety of methods that target a particular sports-relevant skill with the aim of improving it 'off-field', in isolation, to then transfer to improved performance on the field.

One of these perceptual skills is *decision-making*. Broadly, effective sports decision-making entails being able to detect and identify options within the sporting landscape, with the intention of selecting and executing the one that best suits the current task demands, within a suitable timeframe. Many elite sports are dynamic and interactive, and entail a large amount of complex decision-making; shot selection, where and when to pass, which way to move, and more. Previous work has shown that decision-making can be improved with training (e.g. Alder et al., 2016), and skilled athletes make better decisions than unskilled ones (e.g. Roca et al., 2013). Good decisions then lead to better outcomes, so it has long been argued that when all other attributes are equal, effective decision-making is the difference between truly- and nearly-elite athletes (Reilly et al., 2000). Effective decision-making requires tactical awareness (i.e. perception of information) and an understanding of how to react, in terms of both knowledge-of the game (Ashford et al., 2020) and knowledge-in the game (Sullivan et al., 2021). An MPT that targets decision-making is therefore attempting to improve a trainable and important sports-related skill; the important remaining question is then whether such 'off field' training transfers to performance in the real-world version of the sport.

Transfer occurs between training and test tasks to the extent that these tasks are similar along a meaningful dimension ('similar' is a complicated notion, which we will discuss below). An MPT technology that seems likely to offer the right kind of similarity for sport is *virtual reality* (VR; Craig, 2013), or more generally, *virtual environments* (VE; Gray, 2019). A virtual environment is a simulation of a task or scenario that is typically presented to the user or users via an immersive display. Users can typically interact with the display, by having their movements tracked There are many ways to implement these systems (e.g. head-mounted displays, immersive CAVE systems; Gray, 2019 and Miles et al., 2012 have more details on the various options).

This technology allows athletes to be presented with realistic and interactive scenarios of varying complexity and be required to respond in a number of task-appropriate ways. This offers several potential advantages over real-world training, including easier manipulation of task constraints and task difficulty, the addition of augmented feedback, and more repetitions of a scenario that may be rare or hard to create in the real world (Gray, 2019). Given these opportunities, there are indeed VR sports decision-making training systems being developed, and a small but growing literature testing these for effectiveness.

The purpose of this scoping review is to evaluate the literature using VR to train decision-making in sports contexts. We will examine the evidence for transfer of VR training to on-field performance, and identify best-practice design principles for future research on this topic. The broad result of this review is that (a) a wide range of immersive technologies are being increasingly used to train sports-related decision-making processes, and (b) there is indeed some evidence for learning and transfer of learning to the real world. However, there is as yet little programmatic work on this topic, and there are many gaps in the knowledge we have gained about how best to design and test these systems. Overall, applying immersive technology to decision making in sports seems both possible and promising, which makes the large amount left to do more of an opportunity than a problem.

This paper will proceed as follows. First, we will discuss the topic of transfer of learning, and the long-standing difficulty in defining when two tasks are 'similar' enough to expect learning to transfer between them. This will lead to a recent and promising theoretically motivated framework for assessing similarity of MPTs to their actual sport in meaningful ways, the ecological Modified Perceptual Training Framework (Hadlow et al., 2018). We will use this framework to evaluate the papers included in the review (and then also evaluate the framework itself by how well it guides this assessment). Finally, we will summarise the evidence for the conclusions described above and make specific proposals for future directions for research in this field.

Transfer of learning

The goal of any type of sports training is for that learning to *transfer* from the training scenario to the real world, match day version of the sport (Broadbent et al., 2015). The focus is transfer because, as a rule, training is never identical to the full game dynamics, but rather focused on some *part* of the *whole*. One way to develop successful MPT systems is to simply build them and test them; if transfer is observed then the system is a good one. While this testing must be part of the evaluation of any training technology, it is also important to constrain the design process in a meaningful and efficient manner.

Learning is predicted to transfer (from a *transfer task* to a different *criterion task*) to the extent that the two tasks overlap in some meaningful way (Pinder et al., 2011). By definition, this overlap is less than complete; if the two tasks are identical then you are assessing learning, not transfer. The question then becomes, how to formalise a notion of *task similarity*, and this, historically, is where the problem lies. Even seemingly small changes in task elements can prevent transfer; for example, training on a pursuit-rotor task at one speed fails to transfer much when the speed is increased (e.g. Lordahl & Archer, 1958), while learning to balance on a beam does not help balance on a slack line, or vice versa (Serrien et al., 2017). The surprising result of decades of research is that learning is very task-specific, and that we do not yet have the right framework for evaluating task similarity (discussed in Leach et al., 2021a, 2021b; Schmidt & Young, 1986). This makes it particularly difficult to design any modified perceptual training system like a virtual environment, in which everything about the task must be specified by the researcher.

The topic of formalising task similarity has swung in and out of the literature since Thorndike and Woodworth (1901) first addressed it scientifically. As reviewed by Leach et al. (2021a, 2021b), the problem has been that each time it has been addressed, task similarity has been conceptualised using intuitions expressed in everyday language (e.g. balancing on a beam and balancing on a slack line both entail 'balance', so the tasks overlap there) and this has simply never worked (these tasks do not overlap because no transfer of learning is observed between them). We need to find a better method of assessing task similarity.

The topic of task similarity is back in researchers' discussions, using a less circular understanding of similarity. Parts of a task are now identified, not on intuitions, but based on the formal elements from the ecological approach to perception and action, specifically *affordances* and *perceptual information* (e.g. Gibson, 1979). In the experimental literature this analysis is called an *ecological task-dynamical analysis* (Bennett et al., 2024; Leach et al., 2021a, 2021b; Snapp-Childs et al., 2015), while in the particular context of sports coaching it is referred to as *representative learning design* (RLD; e.g. Pinder et al., 2011). Usefully, for the purposes of this review, this latter approach has inspired the development of a framework for evaluating modified perceptual training tools in terms of transfer (Hadlow et al., 2018), which we will use to structure our discussion of the papers included in the review.

The modified perceptual training framework (Hadlow et al., 2018)

Modified Perceptual Training (MPT) is the name for sports training tasks that have been specifically designed to improve a perceptual skill in an athlete in an 'off field' manner. It covers a broad variety of methods that target perceptual skills assumed to be important for sports performance without just training on the sport itself. Hadlow et al. (2018) note that in order for an MPT to be useful, (i) it has to target a skill that actually affects sports performance, (ii) that skill must be trainable, and (iii) the training should transfer to improved performance on the field. They then propose their Modified Perceptual Training Framework (MPTF) as a method for guiding the design and evaluation of MPTs, specifically to identify the degree to which transfer is expected.

Hadlow et al. (2018) ground their framework in RLD (Pinder et al., 2011), which in turn is grounded in the ecological approach to perception-action (Davids et al., 1994; Gibson, 1979) as well as Brunswik (1956). A learning session is *representative of* (i.e. usefully similar to) the target transfer context if it includes the various interacting ecological constraints (e.g. affordances) that context imposes on behaviour, especially by including the perceptual information that context would create; and by preserving a functional perception-action coupling in the behaviour of the person being trained:

> Therefore, RLD highlights three interacting factors important for the design of effective practice tasks; (1) perceptual processes that link, (2) information to (3) action, which align with the three identified factors that differentiate MTP tools (1) targeted perceptual function, (2) stimuli and (3) response mode, respectively. Hadlow et al., 2018, p. 955

Effectively, Hadlow et al. (2018). have used RLD to theoretically motivate the dimensions along which to evaluate the similarity of two tasks (here, a perceptual training task and the sport it is designed for). In this paper, we have used the MPTF as a guide for evaluating the papers included in the review. In addition, we wanted to evaluate how useful the MPTF had been, which we will return to in the Discussion.

We can therefore ask three questions of any perceptual training protocol, and place answers to each along a continuum, and the MPTF predicts that the more similar a perceptual training system is to the actual sport on *these* dimensions, the more transfer you would expect:

- *What is the perceptual function targeted by training?* This addresses the question of 'what is being trained?'. The dimension ranges from basic visual skills (e.g. contrast sensitivity, acuity) through more complicated but still generic skills (e.g. hand-eye coordination) to advanced perceptual-cognitive skills that are more sport- and context-specific (e.g. sport-specific decision-making).

- *How similar are the stimuli in training vs competition?* This is essentially a question about the quality of the perceptual training system, but split into two components. First is *visual correspondence* (how photo-realistic are the stimuli), the second is *behavioural correspondence* (do the stimuli act the way they do in the real world). This framework proposes that both high visual and behavioural correspondence are required for good transfer (although the effectiveness of point light displays as stimuli for studying perception suggests behavioural correspondence may be more important; Blake & Shiffrar, 2007).
- *How similar is the response required in training to what is required in competition?* This continuum ranges from generic responses (e.g. verbal, button pressing) to sports-specific responses (e.g. swinging an actual baseball bat).

To summarise: there is a long-standing interest in using modified perceptual training systems to improve sports performance, and virtual reality is a promising technology for implementing these systems. One important target of such systems is decision-making. The goal of this review is therefore to use the MPTF to evaluate the current state-of-the-art in using immersive technologies to train sports decision-making, and to also identify best practices for designing and evaluating such systems to guide future research.

Methods

Development of search strategy

We developed the following search string:

> ("virtual" OR "virtual realit*" OR "virtual environment*" OR "virtual world*" OR "virtual system*" OR "virtual partner*" OR "virtual Immers*") **- In Title**
>
> AND
>
> ("sport*" OR "exercis*" OR "physical activit*" OR "Decision Making" OR "Motor Skill" OR "Motor Task" OR "Motor Learn*" OR "Skill Acquisition" OR "Cognit*")
>
> **- In Title & Abstract**
>
> NOT
>
> ("Rehab*" OR "Stroke" OR "Patients" OR "Surgery")
>
> **- In Title**

We ran the search in three different databases: SPORTDiscus, PubMed, and Psycinfo, at two times; 11th October 2022 and we updated the search on 12th July 2024.

Inclusion/exclusion

Papers were included if they were (i) written in English, (ii) examined VR[1] in sports players, (iii) measured a healthy cohort, (iv) measured perception & action in some objective method and (v) measured decision-making in some capacity. Given the wide variety of ways decision-making is conceptualised in the literature, we simply required tasks that presented participants with a sport-specific scenario and involved selecting between two or more sport-specific options before acting; making a decision that might actually arise in the sport (e.g. pass or don't, defend or don't). Papers were excluded if (i) they were written before 1990, (ii) not written in English, (iii) a dissertation or review paper, (iv) no VR used or (v) not sports related. The first exclusion criterion was simply a pragmatic decision, as we did not expect to find any papers using modern VR technologies in this area prior to then,

After applying these inclusion and exclusion criteria to the Title and Abstracts, 133 papers were left. The full articles were then read and a further 105 papers were removed. The majority of these were easily removed as they clearly did not fit the inclusion criteria. For papers that were less clear, three of the researchers (JC, DA, ADW) came to a consensus on whether or not it fit the inclusion criteria. This left 13 papers. One of these (Petri et al., 2019b) was excluded because the relevant data was also reported in a second paper (Petri et al., 2019a); we included just the latter as it was a more comprehensive paper.

Finally, we examined the reference lists for the 12 remaining papers as well as who had cited these papers, to find any other potential papers the initial search string may have missed. This led to an additional 861 papers. We removed 775 based on the Title and Abstract, and 73 after reading the papers, by applying the inclusion and exclusion criteria. This left us with an additional 13 papers the search string had not caught.

In total, we were left with 25 papers included in the review (flow diagram and a full list and breakdown are in the Supplementary Material; https://osf.io/rgq9z/).

Hadlow et al. (2018)'s Modified Perceptual Training Framework (MPTF) assesses training systems across three separate dimensions: Targeted Perceptual Function, Stimulus Correspondence, and Response Correspondence. We ranked papers on each of the dimensions, by assigning each paper a number from 1-10; the goal was simply to rank order the papers to guide our discussions, rather than develop any kind of objective scoring system. Rankings were subjective but constrained by the descriptions in Hadlow et al. (2018). Two of the authors (JC, DA) independently ranked these studies along the dimensions and then discussed and agreed associated ranks. Finally, these ranks and rationale were discussed and agreed upon with ADW. We discuss specific examples in the sections below to illustrate how we operationalised each dimension.

Data availability

Data sharing is not applicable to this article as no new data were created or analysed in this study.

Results

Across the two searches, we identified a total of 7050 results before 1471 duplicates were removed, leaving 5579 unique papers to be screened for eligibility.

Type of virtual reality (VR)

Virtual reality is a term which encompasses several distinct technologies that vary in their capabilities. The first finding of our review is that researchers vary in what technology they consider to be VR – there were four main types:

1. *Immersive 360° videos:* Typically experienced through a headset with a device like a phone, these videos lack interactivity, meaning the participant's actions do not affect the content of the video. However, they do allow for active visual exploration, granting participants the freedom to choose where to look and when.
2. *Large projection screens:* These screens can either be a single display in front of the participant or part of a CAVE system that includes screens on each side, enhancing the immersive experience. Stereoscopic glasses are often used to provide depth perception. These systems also track the participant's movements, not only to adjust the display according to the viewing position but also to make the virtual environment responsive to the participant's actions.
3. *Head-mounted displays (HMDs)*: These devices project stereo views of a virtual environment onto two screens, one for each eye. They utilise integrated head-tracking to enable visual exploration of the virtual scene. Furthermore, they can be coupled with various sensors to track participant motion, creating a fully immersive and interactive experience.
4. *Augmented reality displays (AR)*: These devices are headsets that allow the user to see-through to the real world, but that can then superimpose virtual images onto that view.

Of the 25 papers included, seven used 360° videos presented within a head-mounted display; six used a CAVE like system, varying in the number of projector screens and the use of stereoscopic glasses; two used 360° videos and a virtual environment; nine used HMD systems such as the Meta/Oculus Quest and the HTC Vive to present a virtual environments; and one used augmented reality (Microsoft Hololens) (see the Supplementary Material for a breakdown).

This is quite a wide range of technologies, with a wide range of capabilities. 360° videos are not interactive, for example; the user can only observe the display. They do provide more options than a screen-based presentation, however; users can actively visually explore the scene as they see fit, via head and eye movements both. For the purposes of this review, we have included these papers because the researchers considered the technology to count as virtual reality, and we consider this wide variability in use of the term 'virtual reality' to be an important result of this review. But it is clear that a more precise taxonomy of displays is required, and we will return to this point in the Discussion.

Modified perceptual training framework classifications

In the following sections, we will describe the MPTF dimensions and describe how we applied these to exemplar papers. We will then focus on the central question, whether VR training shows evidence of transfer to the real world.

Targeted perceptual function

The Targeted Perceptual Function was kept constant in our review as we were only interested in papers which assessed decision-making in sports, which would be placed high on this continuum. We have therefore already removed any variation here and we won't examine this dimension further.

Stimulus correspondence

Stimulus Correspondence examines how similar the stimuli presented in the MPT is with the stimuli in competition. This is influenced by (1) Visual Correspondence and (2) Behavioural Correspondence of the training. Generic stimuli (e.g. a coach shouting a number, or holding up a certain number of fingers for a particular player to respond to) are ranked at the low end of the continuum and sport-specific stimuli (e.g. a player responding to an opponent's movement within a game-like context) are ranked at the higher end.

Visual Correspondence. VR's Visual Correspondence is influenced by the graphical quality of the technology used. As can be seen in Figure 1, most of the included studies ranked highly on Visual Correspondence, showing that researchers are taking advantage of the graphical opportunities of modern VR systems. For example, Fortes et al. (2021), ranked highest on Visual Correspondence as their participants used HMDs to watch a video or real gameplay recorded on a Go Pro Hero 3 camera; the display moved realistically due to it being a video. Gray (2017) also ranked high on this dimension as his participants attempted to swing at a virtual baseball which was projected to them on a single screen (horizontal = 2.11 m, vertical = 1.47 m), whereby they saw the pitcher, the ball and the field. The graphic quality was ranked high as a rate of 60 Hz was used projecting onto a high-end projector (Proxima 6850+ LCD).

There was of course some variation. Vignais et al. (2009) explicitly manipulated Visual Correspondence across five levels within a virtual setting, hence that paper covered a span along the dimension. They found that graphical quality did not impact basic measures such as reaction time or accuracy, but that it did affect the execution (kinematics) of the response.

Alt et al. (2021) and Watson et al. (2011) ranked lower than the rest on this dimension, while still being rated above the midpoint. For both papers, the lower rank for Visual Correspondence is due to the images provided in the paper, whereby the fidelity and graphic quality of the virtual environment looks less advanced than the other studies.

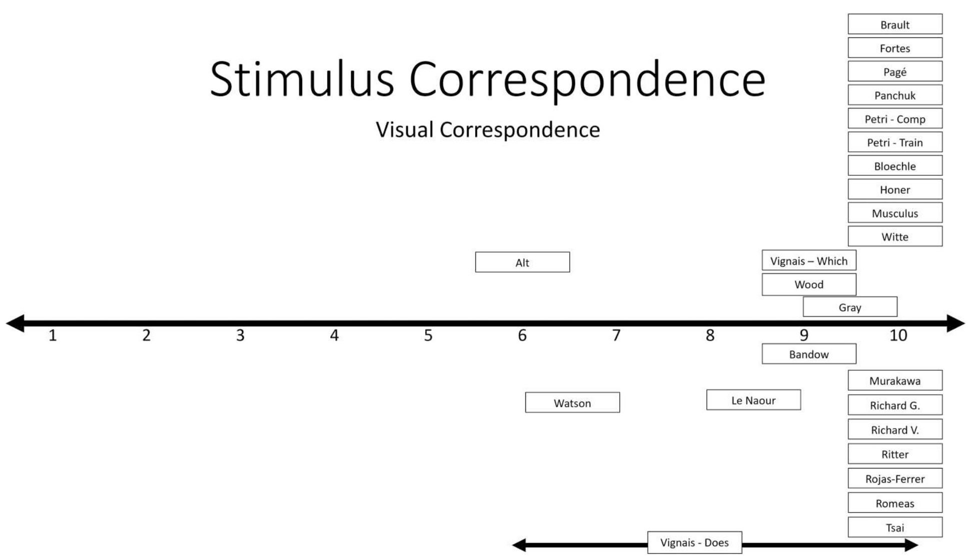

Figure 1. Rankings of included papers on the Visual Correspondence dimension of the Modified Perceptual Training Framework.

Behavioural Correspondence. The Behavioural Correspondence in VR is influenced by how realistically the virtual avatars and environment move and respond. As can be seen in Figure 2, most of the included studies ranked highly on Behavioural Correspondence, showing that researchers are again taking advantage of the graphical opportunities of modern VR systems.

Combat sport papers by Bandow et al. (2014) and Petri et al. (2019a, 2019b) were ranked highly on this dimension as they used motion capture of real movement to create their virtual avatars, meaning they moved exactly as a human would. Other papers used real-life video footage displayed through CAVE or HMDs, which shows real people moving as they normally do (Fortes et al., 2021; Richard et al., 2022).

Alt et al. (2021) and Watson et al. (2011) were ranked lower here because their lower Visual Correspondence limited what they could make their displays do. Alt mentions 'two computer-controlled virtual human opponents appeared … and started moving towards the participant at a constant speed and on a fixed diagonal trajectory' (p. 378); this is not how humans/ avatars mimicking human behaviour behave. Rojas Ferrer et al. (2020) used high-quality graphics, but their focus appeared to be on the fidelity of the environment, including the presence of crowd noise and graphical detail of the stadium. With no mention of motion capture or explicitly stating how the virtual avatars moved within the environment we placed this slightly lower than the rest of the studies.

Wood et al. (2021) compared four different scenarios in their study, and one way these varied was how realistically the VR display behaved; hence this study covers a range along this dimension. For example, in one scenario (the 'Pressure Pass') teammates/opponents are placed on hemispheres and remained static, resembling Subbuteo, which is not how players move in the real game. However, in other scenarios, the virtual avatars acted more realistically. They did not analyse their data to see how this variation affected

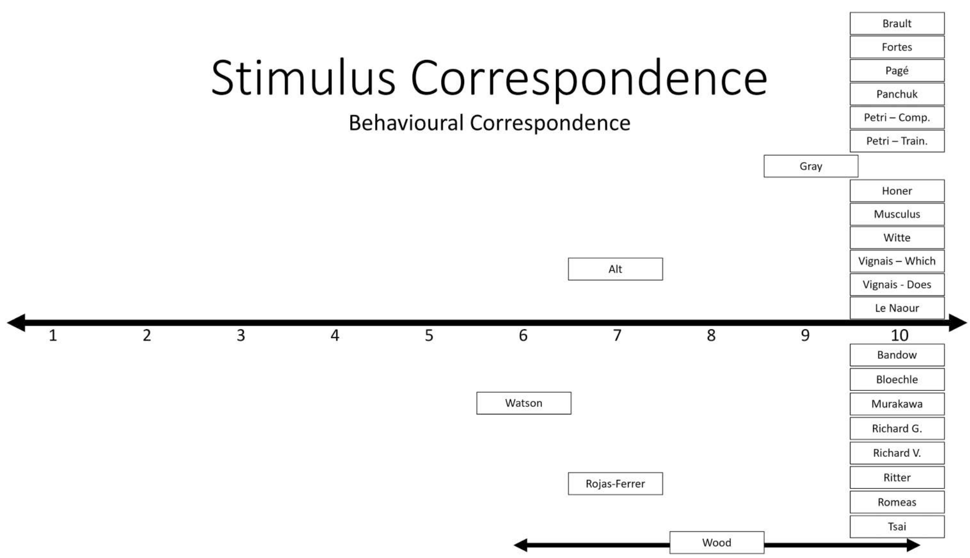

Figure 2. Rankings of included papers on the Visual Correspondence dimension of the Modified Perceptual Training Framework.

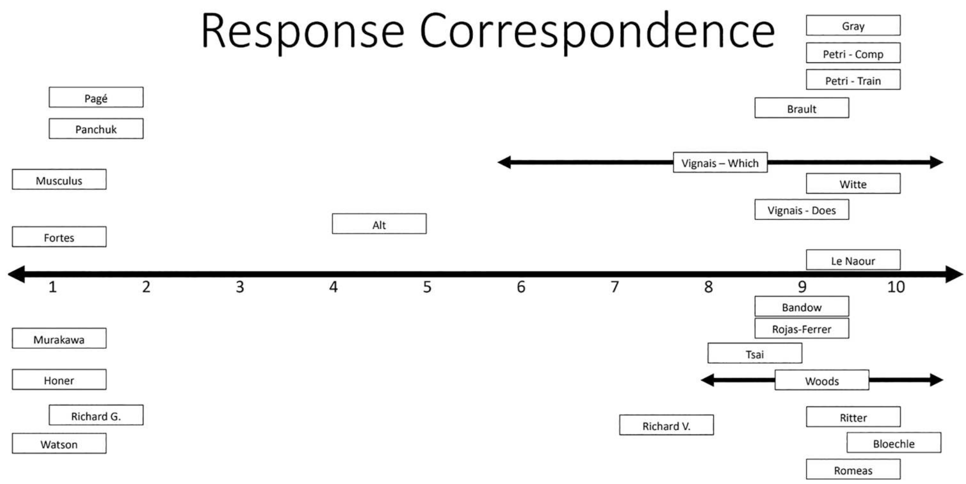

Figure 3. Rankings of included papers on the Response Correspondence dimension of the Modified Perceptual Training Framework.

performance, however; their focus was on showing their system could differentiate between differently skill level players.

Overall, there was limited variability on either element of stimulus correspondence, with most studies ranking quite highly on both dimensions.

Response Correspondence. Response Correspondence addresses how similar the primary type of response required when performing MPT is to the typical natural skill execution performed during competition. As can be seen in Figure 3, although VR technology lends itself to allowing sport specific responses, there was much more variation here. Several of the studies reviewed used verbal and other generalised responses (Fortes et al., 2021; Pagé et al., 2019; Panchuk et al., 2018; Richard et al., 2022; Watson et al., 2011). For example, Watson et al. (2011) used a button response for their participants. Halfway along the dimension, Alt et al. (2021) had participants orient their body in the direction they wanted their avatar to go but not carry out any other movement related to the task.

Many papers did rank high on the dimension, though, by having their participants acting as they would in real life scenarios. Gray (2017) had athletes swung a baseball bat as they normally would, while Romeas et al. (2022) had their boxer participants wear an HMD and respond to a video of a boxer in a ring. Their response was exactly how they would strike and evade their opponent in the real-life event.

Transfer of learning

The MPTF predicts that a technology or study that ranks highly on all their dimensions should produce more transfer of learning out of the virtual training environment and out into game performance compared to those who rank lower across the dimensions. Only six of the 25 papers assessed transfer; we will evaluate their results relative to their performance in the MPTF (and later discuss the fact there were only six).

As mentioned above, the Targeted Perceptual Function was kept constant. All six papers also ranked highly on both Visual and Behavioural Stimulus Correspondence dimension. There was, however, variation in Response Correspondence, with two clear clusters forming. Three of the papers (Cluster 1: Gray, 2017; Petri et al., 2019b; Witte et al., 2022) ranked high by having participants respond in a sports-specific manner, while three papers (Cluster 2: Fortes et al., 2021; Pagé et al., 2019; Panchuk et al., 2018) ranked low by having participants respond verbally or simply observing the content. The MPTF predicts that studies in the first cluster should elicit more transfer than studies in the second cluster.

Cluster 1. Two of these papers (Gray, 2017; Petri et al., 2019b) displayed positive transfer effects, although each only showed this in specific conditions. Witte et al. (2022) showed a very small improvement in VR performance with VR training, but no transfer to the real world; it may be that there simply was not enough learning for transfer to be apparent in the data.

In Petri et al. (2019b), generic reaction times & motor response times showed no significant improvements following training. However, there were significant improvements in a karate-specific movement analysis when comparing the intervention to the control. This suggests the VR karate training was, indeed, sufficiently similar to the real karate context, as the MPTF ranks suggest. It also points to the task-specific nature of training benefits, as discussed in the Introduction.

Gray (2017) tested two different VR training protocols against a control group and a real baseball swinging practice. The first was Basic batting practice in VR whereby participants had 30 trials at batting 'attempting to hit the ball hard over the infield.'. The protocol was similar to real-life batting with pitch type (Curveball, Fastball & Changeup) blocked for 10 trials for each session. The pace of the pitch was increased after every three sessions. The second was Adaptive training – here, participants also faced 30 pitches a session, but each individual pitch was set at the participant's skill level (the challenge point principle; Guadagnoli & Lee, 2004). This was done using a staircase procedure for each type of pitch, whereby the challenge point was increased or decreased based on the previous success rate of a pitch an optimal point was found. This adaptive style of training is not possible in real batting practice. The results showed that adaptive VR batting elicited transfer to the real world, while the non-adaptive VR batting did not. This suggests that simply performing multiple hits in VR does not elicit effective transfer in performing real-world batting. These results also demonstrate another potential benefit of using VR, being able to adapt the training in real time according to the player's performance.

Cluster 2. In the second cluster which displayed high scoring on stimulus correspondence and low scoring on response correspondence, results were also positive but inconclusive.

Pagé et al. (2019) did show transfer but on a fairly limited task. Their task involved training basketball players on selecting where to move to help score from a play, out of four options (move left, right, forward, or stay put). The VR condition used immersive 360° videos presented on a smartphone in an HMD, while the computer screen condition used more restricted videos presented on a monitor. Those trained in VR made better decisions in real world, on-court scenarios in both trained and untrained scenarios, while those trained on the monitor only improved for trained.

Panchuk et al. (2018) trained participants on a similar decision-making task, this time only using 360° immersive videos presented via a smartphone in an HMD. They saw improvement in the task with training (although the female control group also improved). They usefully assessed transfer to a small-sided game, but with very mixed results; the female control group and the male training group both showed improvement, although nothing was statistically significant. The small sample size and erratic pattern of results makes it hard to draw strong conclusions.

Fortes et al. (2021) used a similar design to Pagé et al. (2019), this time in football. Participants were trained on passing decision-making with either 360° immersive videos, or non-immersive videos on a computer monitor. The transfer was assessed with measures of performance in 3 × 3 and 5 × 5 small-sided games. Across measures of passing decision-making and gaze behaviour, they replicated the result from Pagé et al. in which both training groups changed but the VR training group changed more (to slightly more fixations of slightly shorter duration). However, it was unclear whether the changes in gaze behaviour counted as improvements; in the Introduction they suggest higher skill is associated with fewer fixations of longer durations, in the Discussion they suggest the opposite (matching what they found). So while the more representative VR training did have more effect, more needs to be done on what the changes mean.

Two of the three Cluster 1 papers (with high Response Compatibility) showed clear patterns of transfer of what was trained in VR. Cluster 2 papers (with low Response Compatibility) showed a much more mixed pattern, with less consistent evidence of transfer. With only six papers assessing transfer, we do not want to draw strong conclusions, but just to note that the pattern is broadly in line with the predictions of the MPTF (Hadlow et al., 2018). It is worth noting, however, that Cluster 1 used interactive VR technologies, while Cluster 2 all used 360° video; this may be another factor explaining the results.

Discussion

The results of this review and evaluation revealed three main findings. First, there is interest in using VR to train decision-making in sports, as evidenced by the number of papers we found; second, there is at least some evidence that this training does help, by transferring outside the virtual training space. But third, there is as yet no coherent programme of research, or even agreed upon methods and analyses, and few studies even studied transfer (which is the goal of such training!). The included studies, while interesting, do not (yet) solidly build to a strong case in favour of using virtual environments to train decision-making (versus, for example, just training it in the real world). The practical upshot is that there is reason to think the technology has promise, but there is still a lot of work to do to figure out how best to fulfil that promise.

We recommend that this future work follow the recommendations of Gray (2019) and the example of Gray (2017). This latter study stood out to us as an exemplar of best practice in researching the capabilities of training in virtual environments for transfer to the real world, so we will highlight the key elements here now.

First, Gray (2019) identified two criteria for evaluating the use of a virtual technology in training a sports skill. The primary criterion is simply whether or not there is positive transfer of the learning from the virtual scenario to the real environment. He then notes that every other criterion for evaluating the technology (fidelity, immersion, technical specifications) should only be of concern to the extent they are shown to have consequences for transfer. This is worth highlighting: it is the entire purpose of using these technologies, but we found only six of 25 papers actually tested for this transfer! Future work should be expected to test this transfer as an absolute minimum requirement.

The research programme implemented by Gray (2017) then serves as a concrete guide to implementing this programme. First, assessing transfer was central to the design, via both *near transfer* (to a nearly identical real-world batting task) and *far transfer* (to on-field performance, measured here with the on-base percentage in real games over 5 years). Second, Gray tested two different ways of implementing the virtual training, to identify which opportunities offered by the use of virtual (over real-world) training mattered for transfer. The main result was that the adaptive training that is possible in VR but not in the real world was the main benefit, which speaks directly to the question of the value of VR over real-world training. Finally, Gray included four experimental groups; two VR training groups (adaptive vs non-adaptive training), a real-world non-adaptive training group, and a control group. This again enabled Gray to assess not just whether VR training had benefits, but how those benefits compared to real-world training. This is the only question that really matters for this technology, and so it should be explicitly included like this in the design of future research.

How useful is the modified perceptual training framework?

Research that develops an MPT needs a guide; some reason to believe that the features included in a training system are, in fact, the ones that matter for improved performance on the field. As we discussed in the Introduction, transfer has been very hard to predict because the existing frameworks have not included the relevant features. More modern frameworks grounded in the ecological approach (e.g. ecological task dynamics; Leach et al., 2021a, 2021b; representative learning design; Pinder et al., 2011) have demonstrated real promise, and the Modified Perceptual Training Framework (Hadlow et al., 2018) is an explicit method for evaluating the potential of training to transfer grounded in the ecological approach. We therefore used the MPTF as a guide in evaluating the papers included in the review. As a secondary aim, we wanted to then reflect on how useful it had been as a guide.

The MPTF certainly worked to guide our evaluation of the papers. It provided clear and justified questions to pose, and also provided a way to sensibly illustrate the variability we found in the use of VR. In addition, in the six papers that tested transfer, those with high Response Compatibility did show more consistent positive transfer, in line with the MPTF prediction. Overall, we found that the MPTF provided a useful guide that helped make us be explicit and transparent about how we were evaluating the papers.

However, as we used this MPTF, we did note two limitations. First, the description of the Visual Correspondence dimension is quite focused on image realism. This led us to rank 360° videos quite highly on this dimension (they depict sport-specific scenes with realistic graphical quality); but they lack stereo presentation, for example, which may still matter. This dimension is still somewhat based in intuitions about what a scene should contain, rather than a formal visual information analysis. These intuitions are based in representative learning design (e.g. Pinder et al., 2011) but we recommend complementing them with the formal elements of ecological task dynamics (e.g. Leach et al., 2021a, 2021b) in the future.

Second, we note that one key ecological notion was missing; that of perception-action coupling. The MPTF separates the perceptual aspects of the display and the action aspects of the task into two separate dimensions, but the important ecological element is whether people are performing responses coupled to information relevant to that response. For example, swinging a baseball bat to hit a virtual moving ball is highly coupled; a sports-specific action being coordinated with respect to action-relevant information. Swinging a baseball bat in response to a beep shows low coupling; it is still a sports-specific action, but it is not being coordinated with respect to action-relevant information. Coupling matters. This may help address the above concern that we ranked immersive 360° quite highly on both Visual and Behavioural Correspondence. Given that these videos are high quality and show actual sports behaviour, this aligns with the MPTF as it stands; however, simulated virtual environments support high coupling, while immersive videos do not, and this may have influenced the pattern of transfer results. Considering this aspect may help address the different capabilities of these technologies).

Overall, we found the MPTF useful in making us be as explicit as possible about what we thought a good MPT technology should include, and we think future VR research would find value using it to help situate their work. However, the MPTF would clearly benefit from more engagement with developments in the empirical literature on transfer (e.g. Leach et al., 2021a, 2021b) and with the emerging discussions around what counts as virtual reality (e.g. Gray, 2019) in order to offer more specific guidance and help.

What counts as 'virtual reality'?

This raises one final issue, specifically the use of the term 'virtual reality' in the research literature to cover technologies from 360° videos, to large projection systems, to fully simulated environments. These technologies are not equivalent and equating them under a single term seems like an error. However, clearly delineating the field remains a problem (e.g. Kardong-Edgren et al., 2019). There are three generally accepted features in the computing literature; presence, interactivity, and immersion (Walsh & Pawlowski, 2002), but exactly how to operationalise and measure these concepts remains highly variable. There is also some work considering how to understand virtual environments from a behavioural point of view, using the tools of ecological psychology (e.g. Baggs et al., 2024; Stoffregen et al., 2003); this type of work is important because part of how VR works depends on how observers perceive and act in general.

However, it was clear from the wide range of use in the papers we have reviewed that there is no clear consensus in the modified perceptual training field (and papers using 360° videos were all described as VR training). Because of the lack of clear criteria, we included work in this review using a variety of technologies described as VR so long as it also assessed decision-making, but we have tried to make the variability transparent to emphasise that future work must engage with the specifics of the tools they use. We therefore believe that it will be worth being more precise in the future, and advocate researchers connect more explicitly with the literature on this topic in order to properly situate their technology.

Conclusion

Immersive virtual environment technology has become cheap, powerful, and offers numerous opportunities for creating interesting and useful sports training. This review revealed that there is evidence that training in these environments has benefits for decision-making in sports, and limited (though encouraging) evidence that this training can transfer into the real world. It is therefore well worth continuing to explore how best to design virtual environments to promote the best learning and transfer; however, we foresee that doing this properly will require a significant step-up in the scale of the research, as compared to what we currently find. We recommend Gray (2017) as a gold-standard example of this research programme, and that future research always include at a minimum (1) a VR training group, (2) a real-world training group, and (3) a control group, as well as at least a measure of near transfer from VR to real-world. Additional manipulations of the virtual training can then be tested against these basic conditions; we suggest that the ecological approach can serve as a valuable theory and guide to discovering relevant manipulations to test.

Note

1. Exactly what counts as virtual reality turns out to be a complicated question. For the purposes of this review, we followed what the researchers identified as counting as VR. We will discuss this issue in more detail in later sections.

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