

Effectiveness and efficiency of virtual reality designs to enhance athlete development: An ecological dynamics perspective

STONE, Joseph <<http://orcid.org/0000-0002-9861-4443>>, STRAFFORD, Ben <<http://orcid.org/0000-0003-4506-9370>>, NORTH, Jamie Stephen, TONER, Ciaran and DAVIDS, Keith <<http://orcid.org/0000-0003-1398-6123>>

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1 **Effectiveness and efficiency of Virtual Reality designs to enhance athlete development:**
2 **An ecological dynamics perspective**

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4 J.A. Stone¹, B.W. Strafford², J.S. North³, C. Toner⁴ & K. Davids²

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7
8 ¹Academy of Sport and Physical Activity, Sheffield Hallam University

9 ²Centre for Sport Engineering Research, Sheffield Hallam University

10 ³Expert Performance and Skill Acquisition Research Group, St Mary's University,
11 Twickenham

12 ⁴D.A.C.Systems Limited.

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14
15 Correspondence concerning this article should be addressed to Joseph Stone, Academy of
16 Sport and Physical Activity, Sheffield Hallam University, A213, Collegiate Hall, Collegiate
17 Crescent, Sheffield, S10 2BP. Tel: +44 0114 225 5413; E-mail: joseph.stone@shu.ac.uk.

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27

28 Abstract

29 A rapidly developing area of research is focused on the use of Virtual Reality (VR) systems
30 to enhance athlete performance in sport. The assumption is that implementation of such
31 technologies will enhance skill acquisition and expedite athlete development. However,
32 application of such technologies for enriching athlete development and performance
33 preparation needs to be efficiently and effectively used by coaches and athletes to save time,
34 energy and other resources in practice and training. Here, we argue that implementation of
35 VR systems needs to be grounded in theory, with learning designs informed by a clear
36 scientific rationale. We discuss how the full potential of VR systems can be utilised through
37 implementing a theoretical framework, like ecological dynamics, to shape their application.
38 We outline how an ecological dynamics framework can underpin research and applications of
39 VR in athlete development through: (i) individualised training and assessment programmes,
40 (ii) supporting exploration of variable and creative practice environments, and (iii), ensuring
41 context-dependent perception and decision making, and actions, where technology permits.
42 An ecological dynamics rationale proposes how VR systems, when carefully implemented,
43 can enrich and enhance learning designs, but can never replace coaching support for learning
44 during physical practice.

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51 **Key Words:** Ecological dynamics, Virtual Reality, sport performance, perception-action
52 coupling, interactive learning designs, practice enrichment

53 Abstrait

54 Un domaine de recherche en développement rapide est axé sur l'utilisation des systèmes de
55 réalité virtuelle (RV) pour améliorer les performances des athlètes dans le sport. L'hypothèse
56 est que la mise en œuvre de telles technologies améliorera l'acquisition de compétences et
57 accélérera le développement des athlètes. Cependant, l'application de ces technologies pour
58 enrichir le développement de l'athlète et la préparation à la performance doit être utilisée
59 efficacement par les entraîneurs et les athlètes. Ceci qu' afin de la nécessité d'économiser du
60 temps, de l'énergie et d'autres ressources pour la pratique et l'entraînement. Nous soutenons
61 ici que la mise en œuvre de systèmes de réalité virtuelle doit être ancrée dans la théorie, avec
62 des conceptions d'apprentissage reposant sur une justification scientifique claire. Nous
63 discutons de la manière dont tout le potentiel des systèmes de réalité virtuelle peut être utilisé
64 en mettant en œuvre un cadre théorique, tel que la théorie de "dynamiques écologiques", pour
65 façonner leur application. Nous décrivons comment un cadre de "dynamiques écologiques"
66 peut sous-tendre la recherche et les applications de la réalité virtuelle au développement des
67 athlètes à travers: (i) des programmes d'entraînement et d'évaluation individualisés, (ii) en
68 soutenant l'exploration d'environnements de pratique variés et créatifs, et (iii), en garantissant
69 une perception dépendante du contexte, ainsi que la prise de décision et les actions, où la
70 technologie le permet. Une logique de "dynamiques écologiques" suggère comment les
71 systèmes de RV, lorsqu'ils sont soigneusement mis en œuvre, peuvent enrichir et améliorer
72 les conceptions d'apprentissage. Mais, elles ne peuvent jamais remplacer le soutien de
73 l'entraîneur pour l'apprentissage pendant la pratique physique.

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78 **Introduction**

79 Since the introduction of virtual reality (VR), rapid growth and emergence of new
80 technologies has enabled individuals to behave and interact in more immersive environments
81 with relative ease and at relatively low cost (e.g., Oculus Rift and HTC Vive) (Düking,
82 Holmberg, & Sperlich, 2018). In sport, increased accessibility and mobility of VR systems
83 has led to a growing interest in their application to develop athlete performance (Cotterill,
84 2018). However, despite the number of sports organisations investing in VR systems, there is
85 currently limited scientific evidence to inform and underpin its application (Neumann et al.,
86 2018; Düking et al., 2018). Most importantly, it is unclear whether VR systems develop skills
87 and expertise beyond the specific practice context in which it is implemented, and how the
88 effectiveness of VR compares to other methods of learning and training. While there may be
89 some benefits for athletes, a judgement needs to be made as to whether VR systems are worth
90 the time, money and effort involved in their implementation. It is important to understand
91 whether such time, money and effort may be better invested in developing enhanced learning
92 designs for athletes during traditional practice designs.

93 In this position statement, we argue that to enable the full potential of VR systems in
94 enhancing athlete performance and development in sport, a theoretical framework is
95 necessary to rationalise applications of such systems to ensure effective and efficient designs
96 of VR environments for athlete development and learning. **To achieve this aim, we build on**
97 **the ideas of Craig (2013), who applied concepts from *ecological psychology* to inform the**
98 **design of experimental research on perception-action coupling using virtual reality systems.**
99 We further these discussions using the relevance of key concepts in *ecological dynamics* (i.e.
100 an integration of concepts from ecological psychology, **dynamic systems theory, complexity**
101 **sciences, constraints-led practice, representative learning design**) to inform the design and the
102 application of VR technologies to enrich the training programmes of elite and developing

103 athletes. Finally, we propose future empirical research which is required to support evidence-
104 based implementation of VR in athlete training.

105

106 **An ecological dynamics approach to guide implementation of Virtual Reality systems in**
107 **athlete training programmes**

108 Craig (2013) suggested how the application of virtual reality could be guided by key
109 concepts from ecological psychology which proposes a “direct” solution to perception and
110 action to help athletes become attuned to specifying information in the environment which is
111 coupled with action possibilities. In this theoretical rationale, perception and action are
112 considered to have a direct and cyclical relationship to support performance (Kugler &
113 Turvey, 1987; Handford, Davids, Bennett, & Button, 1997), the strengthening of which VR
114 training systems can potentially enhance. In this respect, the role of VR technology in
115 learning could be to help learners become attuned to specifying information in a simulated
116 performance environment. This central theoretical principle informs the design of learning
117 environments to facilitate athlete exploration of lawful relationships between perception and
118 action emerging during interactions with a performance environment. An extensive body of
119 research has provided support for the reciprocal relationship between perception and action in
120 sport performance (e.g., Dicks, Button, & Davids, 2010a, 2010b; Pinder, Renshaw, & Davids,
121 2009; Stone, Panchuk, Davids, North, & Maynard, 2015). For this purpose, investigators
122 have worked on the development and integration of novel methods, for example in *in-situ*
123 representative designs (e.g., Dicks et al., 2010a, 2010b), virtual environments (Craig, 2013)
124 and integrated video-ball projection systems (e.g., Stone et al., 2014). These research
125 programmes have all demonstrated the importance of continuous coupling of informational
126 constraints and actions during experimental research programmes and sports practice. Key
127 research findings have shown how athletes can continually integrate perception and action

128 during performance, driven by theoretical advances in skill performance and learning, to
129 inform sports practitioners about the design of practice environments (Davids, Araújo, Vilar,
130 Renshaw, & Pinder, 2013).

131 With regards to the implementation of VR systems in athlete training programmes, a
132 recent systematic review by Neumann and colleagues (2018) indicated that current evidence
133 for their value was less than compelling. While they argued that: "The research findings to
134 date indicate that VR can be a promising adjunct to existing real-world training and
135 participation in sport", they did also note that "Future research would benefit from a
136 theoretical framework of VR application to sport...." (Neumann et al., 2018, p.196). A key
137 problem with existing research on implementation of VR systems in sport, identified by the
138 systematic review of Neumann et al. (2018), was the provision of opportunities for athletes *to*
139 *interact* with key variables in the designed digital performance environments.

140

141 **How VR systems can support interactions of athletes with task and environmental**
142 **constraints in preparation for performance**

143 Here, we propose how implementation of VR systems in sports training programmes
144 could be enhanced by a theoretical conceptualisation from ecological dynamics, emphasising
145 how athletes can interact with task and environmental constraints of a specific performance
146 environment. This theoretical rationale builds on Craig's (2013) ideas for guiding VR
147 research underpinned from ecological psychology. We integrate key concepts and ideas from
148 ecological psychology with those from scientific sub-disciplines of complexity sciences and
149 dynamical systems theory to conceptualise athletes and sports teams as complex, highly
150 integrated, adaptive systems composed of many degrees of freedom (Chow, Davids,
151 Hristovski, Araújo, & Passos, 2011). An ecological dynamics rationale proposes that
152 cognition, perception and action are deeply intertwined in regulating athlete performance in

153 satisfying key constraints (individual, environmental and task see Figure 1). This deeply
154 intertwined relationship is most prominent in skilled individuals such as expert athletes as it
155 supports their continuous interactions with task and environmental constraints (Orth, Davids
156 & Seifert, 2018). Gaining this intertwined relationship between sub-systems of action,
157 cognition and perception, which support interactions with a performance environment, is the
158 fundamental basis for using technologies like VR systems to enrich athlete learning and
159 performance. Interactions with key informational variables in a performance context act as
160 boundaries that shape emergent patterns of behaviour (Anson, Elliott, & Davids, 2005).
161 Interacting constraints designed into a representative simulation of a performance
162 environment provide a framework for the acquisition of functional, goal-directed behaviours
163 in learners. This conceptualisation from ecological dynamics provides a clear rationale for
164 understanding how task and environmental constraints, designed in VR environments could
165 guide each individual performer's interactions and learning possibilities.

166 In an ecological dynamics rationale, dynamical systems theory contributes a
167 functionalist framework proposing how coordination in neurobiological systems emerges
168 between components of multiple independent, but interacting, subsystems (Duarte, Araújo,
169 Correia, & Davids, 2012). The concept of *degeneracy* outlines how system elements that are
170 structurally different can perform the same function or yield the same output (Edelman &
171 Gally, 2001). Hence, degeneracy in sport performance indicates that functionally equivalent
172 actions of athletes can be achieved by structurally different movement system components.
173 Neurobiological degeneracy has been revealed in tasks such as football kicking (Chow,
174 Davids, Button, & Koh, 2008) where participants adapted their use of limb segments to
175 continue to successfully perform a task (e.g. height of a football chip) as constraints were
176 manipulated. Such research evidences how skilled performance is achieved via a dynamical
177 process, regulated by perceptual information available to performers in a performance

178 environment (e.g., for reviews see Vilar et al., 2012; Orth et al., 2012). Hence, practitioners
179 should not be looking for one optimal pattern of coordination towards which all developing
180 learners should aspire, but instead, training should be concerned with a process of individual-
181 constraints coupling (Seifert et al., 2013). Importantly here, this theoretical account proposes
182 how each individual may solve the same movement tasks in a unique way. Hence a standard
183 “one-size fits all” practice schedule could be avoided by using VR systems to individualise
184 task and environmental constraints away from the practice context before athletes engage in
185 physical training. Enhancing athlete self-regulation (of emotional, psychological, perceptual
186 and physical sub-systems) through exploiting adaptive variability is an important
187 performance area that use of VR systems has the potential to enrich in practice.

188 Dynamical system theory also proposes that, alongside individualised movement
189 patterns, variability of movement is functional for performance and should not be seen as
190 detrimental to performance. Movement system variability indicates the functional flexibility
191 needed to respond to dynamic performance constraints. Viewing learners as complex
192 adaptive systems promotes awareness in sport practitioners that an individual learner's
193 coordination solutions emerge from harnessing intrinsic self-organisation tendencies and that
194 periods of movement variability (or instability) should be viewed as an important part of the
195 learning process (Chow et al., 2007). Therefore, the use of VR systems could allow
196 practitioners to manipulate relevant task, environment and performer constraints to facilitate
197 the acquisition of functionally relevant coordination solutions via performer-environment
198 interactions. Next, we outline how such principles could shape the future of VR research and
199 learning design guided by these ecological dynamics principles.

200

201 **Figure 1 about here**

202

203 **Representative Learning Design for VR systems training**

204 Implementation of VR systems needs to achieve learning designs that will support
205 learners, over time, becoming attuned to information through practice in varying performance
206 environments, creating relationships between actions and specific sources of perceptual
207 information (i.e. perception-action couplings; see Gibson, 1979; Michaels & Carello, 1981).
208 'Representative learning design' is a term which theoretically outlines how practitioners
209 designing learning environments might use insights from ecological dynamics to ensure that
210 training task constraints are representative of a particular sport performance context toward
211 which practice conditions are intended to generalize (Davids, Araújo, Vilar, Renshaw &
212 Pinder, 2013). Designs underpinned by a representative learning framework enable the
213 utilisation of affordances (i.e. opportunities for action invited by objects, surfaces, features
214 and terrains) perceived by individuals (Gibson 1979) which are available in specific
215 performance environments. Affordances conceptualise the combining of perception and
216 action, since "perception is an invitation to act, and action is an essential component of
217 perception" (Gibson, 1979, p. 46). Hence, to enable the use of functional perception-action
218 couplings, individuals must identify specifying information variables (i.e. be perceptually
219 attuned to constraints of a performance environment), but also have the ability to scale
220 information to their own action capabilities (Fajen, 2007; Jacobs & Michaels, 2007). A
221 challenge for implementation of a functional framework for VR learning design in sports
222 training and practice (see Figure 1) is to ensure that principles of representative learning
223 design are met by careful consideration of the constraints which are present within such
224 environments (see Pinder et al., 2011b).

225 Pinder, Davids, Renshaw and Araújo (2011a) highlighted two critical features to
226 ensure a representative design, *functionality of perceptual information* and *action fidelity*.
227 *Functionality of perceptual information* enables performers to regulate actions with
228 *information sources that are representative of their performance environment, with action*

229 fidelity being achieved when participants' movement responses remain the same between the
230 simulated (e.g., experimental or training) environment and the performance environment
231 (Pinder, Davids, Renhsaw & Araújo 2011a). These concepts emphasise that applications of
232 VR for skill learning need to implement technology and devices to display information
233 (functionality) and support continuous interactions (fidelity) of a learner in a simulated
234 performance environment. These interactions should be underpinned by integrated cognitive,
235 perceptual and action sub-system involvement within specific task constraints designed in a
236 digital simulation of a performance setting. That is, learners in VR training environments
237 should have intentions to achieve specific task goals, informational variables to perceive and
238 affordances to utilise and actions to regulate during practice. **A lack of representativeness in**
239 **VR learning designs may lead to less faithful simulations of performance environments,**
240 **inhibit acquisition of skills, and weaken transfer to performance in competitive environments**
241 **similar to those observed in previous practice designs tasks (e.g. Barris, Davids & Farrow,**
242 **2013).** Clearly, less representative learning designs in VR practice contexts will lead to less
243 efficient and effective use of training time for athletes and coaches.

244 Functionality of task constraints enables performers to regulate interactions with
245 available information sources that are representative of those sources found in a performance
246 environment. For example, learning environments should include perceptual variables that
247 **sample** informational constraints which performers use to regulate their interactions within a
248 performance environment. Functional **sampling** of representative perceptual information in
249 sport training environments is a considerable challenge for coaches and researchers. For
250 example, in cricket, a bowler's kinematic information during the run-up, which is critical for
251 anticipation (Müller, Abernethy, & Farrow, 2006), is often removed because of ubiquitous
252 use of ball projection machines and concerns related to overuse injuries in bowlers (see
253 Pinder, Davids, Renshaw & Araújo, 2011b). Use of VR systems has the potential to

254 overcome such issues, through regulation of the perceptual information presented, while
255 enhancing representativeness by presenting visual information of the run-up from a
256 performer's viewpoint. For example, VR technology could be used to avoid the limitations of
257 a fixed allocentric viewpoint of participants (see Williams, Davids, Burwitz, & Williams,
258 1994; Helsen & Pauwels, 1993). Researchers have previously demonstrated that participants
259 make faster and more accurate decisions when they are presented with a viewpoint from a
260 performer's perspective (egocentric viewpoint) compared to viewing a live broadcast
261 (allocentric viewpoint) (Petit & Ripoll, 2008).

262 Realistic behavioural responses in virtual environments are suggested to occur when
263 the system induces a sense of presence and the perception that the events are actually
264 occurring (Slater, 2009). A functional VR display solution for enhancing quality of
265 perception-action couplings involves use of a computer automatic virtual environment
266 (CAVE) or head-mounted displays (HMD) (Neumann et al., 2018). Typically, CAVEs are
267 large cubes created with display screens, which the user physically enters and is enveloped by
268 a virtual environment simulating the surrounding informational constraints of performance
269 environments. However, such systems can be expensive and require large amounts of
270 physical space, so HMD, which are smaller, portable and more cost-efficient, but still share
271 similar immersive environments, could be more beneficial (Slater, 2009). Nevertheless,
272 HMD require large amounts of space for athletes to move around in or require the use of
273 equipment such as treadmills to enable movement within a smaller space which can be
274 hazardous because vision of a moving treadmill belt is not available (Neumann et al., 2018).
275 In addition, head movements and perspiration of the athlete during actions can make the
276 HMD uncomfortable to wear, which can itself impact the level of action fidelity and
277 presence. Therefore, while HMD are normally cheaper than CAVE systems, the constraints
278 placed on the athlete using such systems may limit the effectiveness of such learning designs

279 due to limitations on the affordances available for athletes to utilise. However, with the
280 continual development of technology, including wireless high-quality headsets (e.g., HTC
281 Vive Pro) and haptic suits (e.g., Teslasuit), opportunities will emerge to develop more
282 perceptually faithful VR simulations of sport performance environments that meet the first
283 component of effectiveness (functionality of perceptual information) of representative design.

284 Despite advances in visual displays, a fundamental weakness in current
285 implementations is that researchers still typically neglect the importance of action
286 components in analyses. The importance of action in functional behaviour is underlined by
287 Gibson's (1979) statement that: "We must perceive in order to move but we must also move
288 in order to perceive" (p. 223). Here, Gibson (1979) highlighted that, not only is perception of
289 information critical for effective movement, the ability to move is critical to change the
290 perceptual information available to performers. That is why it is critical that VR designers
291 focus on the perceptual information presented in these environments, and the cognitions that
292 athletes use to frame their performance intentions while they are moving within these
293 environments. This recognition of the ongoing, intertwined relations between an athlete's
294 cognitions, perception and action implies how the design of VR performance environments
295 can be adapted according to the task and environmental constraints of a specific sport
296 context. Pinder et al. (2011a) recognised the importance of actions in creating representative
297 environments with the concept of *action fidelity*, which requires the performer being able to
298 re-organise motor system degrees of freedom in practice in the same way as would be
299 required in competitive performance. This key idea questions the use of VR responses like
300 finger movements on digital controlling systems, use of wands in hands or verbal responses
301 to simulate actions (Pinder et al., 2011a). Evidence for the importance of capturing actions
302 was highlighted by Oudejans, Michaels, and Bakker (1997) who examined performance of
303 expert and novice baseball outfielders during two catching tasks. In the first, participants

304 attempted to catch a ball, and in the second participants were merely required to point to
305 where a projected ball would land. Skill differences between participants were only observed
306 when they could act on ball flight information, rather than merely pointing to a landing
307 location. It is critical, therefore, that designs and application of VR systems allow
308 opportunities for regulation of faithful, full body actions/responses. Whilst the extent of some
309 actions may be somewhat limited by current VR technologies, an important future challenge
310 for engineers and technologists is to continue to design and develop systems which can
311 support more representative actions of athletes under different task and environmental
312 constraints.

313 Despite action fidelity (i.e. faithful actions/responses) being a critical component of
314 VR design, importantly, it is not only the ability of VR systems to enable representative
315 movement responses, but also the ability of participants to directly interact with and shape
316 these environments through their movements. Learning is founded on continuous
317 interactions of a learner with a performance environment in successful sport practice
318 programmes. Current VR designs, which limit interactive movements of learners can be
319 circumvented by using immersive technology that affords the capacity for individuals to
320 navigate through an ever-changing environment (Sherman & Craig, 2002) and (re)organise
321 actions relative to information available in the virtual environment. These interactions can
322 enhance athlete self-regulation under different task and environmental constraints in sport by
323 forcing adaptations of emotional, cognitive, perceptual and action sub-systems in individual
324 learners, depending on their needs. It is vital that VR systems provide an interactive
325 environment that invites the perception of presence by ensuring that elements within the VR
326 environment can move or change in response to the ongoing actions of a learner (Baños et al.,
327 2000; Sherman & Craig, 2002). For action fidelity to be maintained in practice, technology

328 needs to be non-obtrusive and light-weight as this allows athletes to interact with
329 environments without behaviour modifications due to such restrictions.

330 For this reason, a key requirement for VR systems is to ensure informational
331 constraints of performance are faithful in the representativeness of athlete-environment
332 interactions over time. In this way, VR systems could be used to constrain the acquisition of
333 appropriate perception-action couplings for an individual athlete, accounting for uniqueness
334 and variability of his/her interactions with sport performance contexts (see [Correia, Araújo,](#)
335 [Cummins, & Craig, 2012](#); [Craig, Bastin, & Montagne, 2011](#); [Watson et al., 2011](#)).

336

337 **Future research areas of VR for skill development**

338 With the continued rapid development of VR systems ([Neumann et al., 2018](#)), we
339 envisage that task functionality and action fidelity **will continue to improve, enabling more**
340 **effective and efficient** learning designs, predicated on a clear theoretical rationale which
341 supports a close coupling of perception and action sub-systems in athletes. The use of VR
342 enables sport practitioners to control and manipulate both the environmental and task
343 constraints in specific and reproducible ways ([Hoffman, Filippeschi, Ruffaldi, & Bardy,](#)
344 [2014](#)). These advances will enable athletes to interact with varying affordance landscapes
345 within the learning environment ([Davids, Güllich, Araújo & Shuttleworth, 2017](#)). **In the next**
346 **sections of the paper we outline the potential advantages** of VR to supplement and enrich
347 current training programs, by careful manipulation of constraints, to enable: (1)
348 individualised training and assessment, (2) development of variability and creativity in
349 interacting with an affordance landscape, and (3), enhance context dependent decision
350 making in representative performance conditions.

351

352 **Individualised training and assessment**

353 Ecological dynamics emphasises that coaches need to individualise training designs
354 which can specify the parameters of functional interactions of an athlete with a simulated
355 competitive performance environment. Equally, elite coaches have highlighted the
356 importance of individuality within training as individuals respond differently to the task and
357 environmental constraints manipulated (Greenwood, Davids, & Renshaw, 2012). Although
358 individualisation is important, it is expensive in terms of human resources and time
359 (effectiveness and efficiency), and would take almost as many coaches as players. For this
360 reason, most sports organisations cannot fully exploit the full potential of an individualised
361 training approach, relying instead on group-based sessions. If VR systems can be developed
362 to understand the **performance solutions needed by individual athletes**, then key constraints
363 can be identified and manipulated to facilitate skill development by encouraging exploration
364 of individual movement solutions. **Hence, for VR systems to be effective they must be able to**
365 **consider the unique interaction of physical, physiological, cognitive and emotional**
366 **characteristics of individual learners, which shape how an athlete solves performance**
367 **problems (Araújo, Davids & Hristovski, 2006)**. Because of variations in each athlete,
368 individual rates of skill development are likely to progress at different time scales (Liu,
369 Mayer-Kress & Newell, 2006). Therefore, VR training systems need to take into account the
370 different rates of learning, growth and maturation processes experienced by individuals
371 during skill development. This could be achieved with feedback provided by continuous
372 learning algorithms to each athlete directly in real time (Kim, Prestopnik, & Biocca, 2013).
373 **One area which could start to explore the effectiveness of such features are self-paced tasks**
374 **such as rowing and cycling where VR systems are more easily designed to ensure coupling of**
375 **perception and action (for a review see Neumann et al., 2018)**. Therefore, research could
376 **focus on how best to individualise training systems while ensuring a representative learning**
377 **design.**

378 A particular focus in developing individualised training programs could involve use
379 of VR in injury rehabilitation. **The use of VR systems may enrich rehabilitation programmes**
380 **so that athletes avoid the boredom of over-using repetitive muscle-exercising regimes which**
381 **dominate current methods.** For example, overuse and repetitive strain injuries could be
382 reduced by athletes strengthening coupling of cognition, perception, and nuanced, subtle
383 movements, without the need for physical loading movements (e.g., repetition of problem
384 solving opportunities without excessive physical loading on the skeletomuscular system). In
385 professional sport, an injured player costs money but does not directly contribute to team
386 performance, which can lead to pressures to accelerate the rehabilitation work or rushing a
387 player back with danger of relapse (Akenhead & Nassis, 2016). **Although rehabilitation**
388 **procedures may focus more extensively on physical exercises, psychological components**
389 **such as perceptual, cognitive or decision making skills have been shown as important factors**
390 **in injury rehabilitation (Heaney et al., 2015).** With VR, functionality of skill (re)acquisition
391 may be enhanced by working on perceptual skills, developing decision making and cognition,
392 as well as self-regulation through simulation of competitive performance scenarios from a
393 first-person perspective (Craig, 2013). Use of VR can help each athlete to maintain
394 functionality of movement during rehabilitation, although with reduced loadings on specific
395 action sub-systems (Gokeler et al., 2016). In this case, reduced action fidelity may be
396 beneficial during the rehabilitation period by reducing (re)injury risk. Indeed, some learning
397 may be better than no learning at all during this highly specific phase of rehabilitation. In VR
398 performance simulations there is no possibility of physical contact with other performers and
399 athletes can use non-injured limbs and fewer degrees of freedom, significantly reducing risk
400 of (re)injury. Use of VR could enhance effectiveness and efficiency of an individualised
401 training program for a rehabilitating athlete before returning to practice on field with other
402 players (often referred to in team sports as 'game conditioning'). **However, further research is**

403 required to demonstrate the value of such an implementation of VR to facilitate rehabilitation
404 specialists, athletes and coaches adopting the methodology to enrich their practice (Katz et
405 al., 2006; Akenhead & Nassis, 2016).

406 An essential element of the application of VR in sports training is transfer from VR
407 environments to competitive performance. Many perceptual training tools assume improved
408 on-field performance, yet investigations of transfer are rare (for an exemplar transfer
409 investigation see Gabbett, Rubinoff, Thorburn & Farrow, 2007). Underpinning VR
410 implementation with representative learning design should enhance transfer between practice
411 and performance. For example, Fitzpatrick, Davids and Stone (2018) demonstrated how
412 manipulations to constraints in training underpinned by a representative learning design could
413 afford the development of the backhand shot in children's tennis. However, transferability of
414 skills, tactical understanding, creative behaviours and diagnostic procedures from the virtual
415 environment to performance context is arguably the important challenge to be evidenced and
416 aligned with existing data on transferability of skills (Tirp, Steingröver, Wattie, Baker, &
417 Schorer, 2015).

418

419 **Development of variability and creativity in practice: Designing specific affordance** 420 **landscapes**

421 An area of potential for VR is facilitating innovative performance behaviours in
422 individual athletes, helping them to explore and develop a wider movement repertoire
423 (Santos, Memmert, Sampaio, & Leite, 2016). An ecological dynamics rationale emphasises
424 the design of affordances for innovative behaviours (thinking, adapting actions and decisions
425 and the pick-up of varied information sources) under carefully managed task constraints,
426 before seeking transfer to practice and then performance in a playing area (Davids et al.,
427 2017). The design of a landscape of affordances for learning, using VR systems, is based on

428 the potential to precisely manipulate specific virtual informational constraints, such as space,
429 time, number of other performers, and locations in a performance area, in an almost infinite
430 number of ways to individualise learning opportunities for athletes. For example, Figure 2
431 provides a scenario which seems simplistic but offers footballers a wealth of opportunities to
432 explore intentionality, perception, action and decision making in utilising affordances in a
433 performance landscape. This scenario could be used to develop subtle preparatory
434 movements, such as (re)positioning, (re)orienting and adapting body angles to receive and
435 pass the ball quickly according to the precise locations of defenders collectively trying to
436 deny opportunities for a penetrative pass. Designing practice tasks to enhance player
437 interactions can support the flow of movement, for example, helping players perceive
438 emergent affordances of the biggest (most inviting) gap left by mobile defenders working
439 together (Correia et al., 2012; Watson et al., 2011). The essential element for VR design here
440 is to ensure availability of a landscape of affordances which promote what Bernstein (1967)
441 called 'repetition without repetition' to enhance dexterity, problem-solving and exploratory
442 behaviours of athletes as performers seek to solve problems and make decisions across subtly
443 different scenarios. From this theoretical rationale, it is argued that subtle variations in VR
444 practice environments will promote the necessary flexibility in performance through
445 continued exploration and self-organisation of action responses as the performer adapts to
446 these changing constraints. Through this continued exploration of their environment,
447 performers will be encouraged to interact and discover different movement solutions to reach
448 the same outcome (system degeneracy).

449

450 **Figure 2 about here**

451 In terms of coaching practice through use of immersive virtual reality, the
452 convergence of (virtual) task, environment and organismic constraints contributes to the

453 regulation and dynamics of human behaviour and can be manipulated to produce exploration
454 of movement variability (Newell, 1986; Araújo et al., 2006). This process is founded through
455 adaptive movement behaviours caused by the establishment, reestablishment and refinement
456 of information movement couplings inherent to the performer (Araújo et al., 2006).
457 Manipulating informational constraints in VR systems could induce phase transitions in
458 individual performers by creating learning environments which drive individuals to a meta-
459 stable region of the perceptual-motor landscape of practice where a strategy of co-adaptation
460 can underpin the emergence of creative behaviours. In this process, the athlete is guided to
461 search appropriate areas of the perceptual-motor landscape during practice, not instructed to
462 form a specific movement pattern considered to be optimal by a coach. If an extensive range
463 of affordances can be designed into learning environments, this could enable learners to
464 explore and develop the intertwined relationship between cognition, action and perception
465 without the physical demands of repetitive actions in a sport. **Importantly, despite VR**
466 **systems offering a range of potential learning environments and manipulations to those**
467 **environments which could enhance creativity, currently the limited availability of haptic**
468 **feedback or ability to interact with physical objects such as balls still limits the scope of such**
469 **training environments. While, currently, vibrations can be designed into VR system**
470 **technology to simulate haptic information from interacting with objects, this is an area that**
471 **future researchers may target for enriching feedback in VR systems.**

472

473 **Context dependent decision making**

474 Sport coaches currently attempt to simulate aspects of competitive performance
475 environments in practice so that athletes can attune to performing in specific situations
476 against particular opponents. Research has proposed the benefits of affective learning designs
477 to enhance the self-regulation of athletes (see Headricks, Renshaw, Davids, Pinder, & Araújo,

478 2015; Runswick, Roca, Williams, Bezodis, & North, 2018). To maximise the potential
479 benefits of VR, the systems could be used to simulate not only representative perceptual
480 information, but also challenging situations which require self-regulation, such as different
481 cultural and social contexts, crowd abuse and noise, varying weather conditions, emotional
482 pressure from specific opponents, and even performing in conditions that require increased
483 levels of self-motivation. For example, VR has been used to facilitate simulations of high
484 pressure environments, such as by inducing anxiety in a cohort of soccer players during a
485 penalty-kick shooting task (Stinson & Bowman, 2014). Introducing elements of competition
486 or pressure in VR learning environments could facilitate individualised management of stress
487 and specified dimensions of competitive anxiety (Parsons & Rizzo, 2008). Through practice
488 in a VR environment, athletes can train for competitions under the specific conditions
489 predicted for an actual event in representative simulations. In this way VR could be a
490 prominent training tool for enhancing specific self-regulation skills in individual athletes,
491 which warrants further investigation.

492 The use of perceptual and cognitive process training has been introduced in many
493 sporting and research environments (Harlow, Panchuk, Mann, Portus, & Abernethy, 2018).
494 **For example, research has attempted to train attention towards specific features of a**
495 **performance environment by occluding or artificially highlighting key performance features,**
496 **such as postural cues of penalty takers when training anticipation skills in soccer goalkeepers**
497 **(Murgia et al., 2014).** However, much of the data generated from these measures have been
498 taken from a reductionist method which removes much of the context (e.g. score line, history
499 of playing against an opponent) from the decision making task. Use of VR environments
500 which introduce varying contextual factors while concurrently measuring gaze and
501 movement behaviours have potential to further understanding of expert perceptual processes
502 (e.g., scanning, attentional and anticipatory behaviours) in representative, context specific

503 performance environments.

504

505 **Conclusion**

506 Use of VR systems in learning design could provide a suitable vehicle for specificity
507 of practice to enrich athlete interactions with simulated performance environments,
508 encompassing cognition, perception and actions in practice. An ecological dynamics
509 framework can underpin the design of virtual environments to support effectiveness,
510 efficiency and efficacy in developing a deep integration of cognitive, perceptual and
511 movement skills during these simulated interactions. The use of VR systems can specify
512 training for individuals by focusing their attention on specific fields within an affordance
513 landscape (Davids et al., 2017). For example, investment in a VR system oriented for the
514 acquisition of expertise in youth football could: (1)enrich athlete performance by
515 individualising training programs which can be complemented with group-based, physical
516 practice contexts, (2) reduce the time to achieve 'game conditioned' status when returning
517 from an injury, and (3), help promote engaged (i.e., motivated and invested) players in their
518 development over prolonged periods of practice. The use of virtual reality in training is not
519 intended to replace the role of sport practitioners, such as a coach, but to assist them and
520 complement on field training by enriching the learning of athletes.

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531 **References**

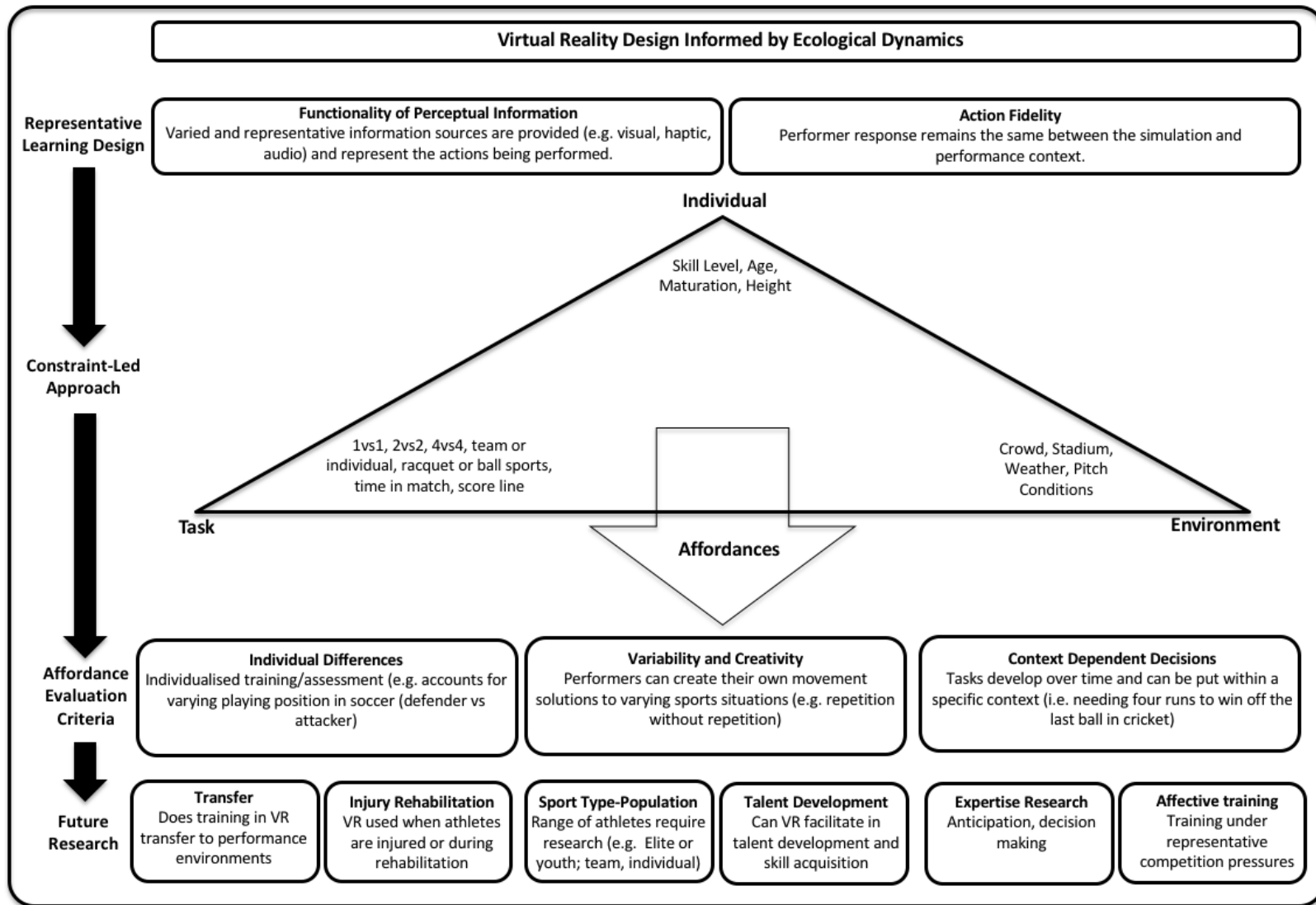
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Figure 1. An Ecological Dynamics framework to guide the use of Virtual Reality in sport and highlight potential future research

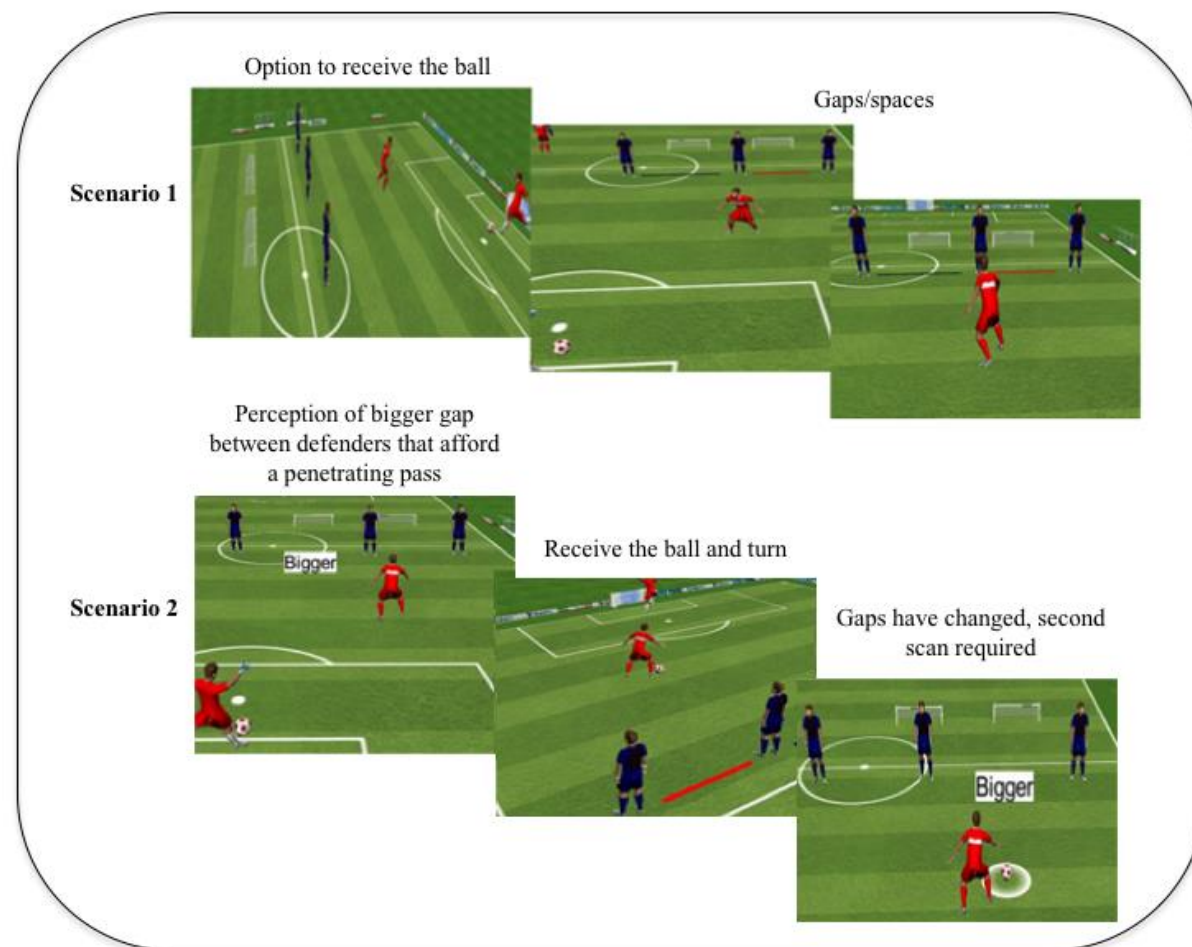


Figure 2. Virtual Reality practice scenarios. Scenario 1: The receiver in red must control the pass from a teammate and turn to play the ball into either small goal area. The task is to find the biggest affordance (gap/space) and play the penetrative pass. Here, the distance between the defender is fixed over time. Scenario 2: The distance between defenders changes over time with more advanced learners needing to perceive the biggest emerging gap.