1   **Virtual Reality in Biology: could we become virtual naturalists?**

2   Authors: Juliano Morimoto[1*], Fleur Ponton[2]

4   Author's affiliations:

5   1 – School of Biological Sciences, University of Aberdeen, Zoology Building, Tillydrone Ave,

6   Aberdeen AB24 2TZ, United Kingdom

7   2 - Department of Biological Sciences, Macquarie University, NSW 2109, North Ryde,

8   Australia

10   *To whom correspondence should be addressed:

11   Juliano Morimoto

12   School of Biological Sciences, University of Aberdeen, Zoology Building, Tillydrone Ave,

13   Aberdeen AB24 2TZ, United Kingdom, e-mail: juliano.morimoto@abdn.ac.uk

15   **Abstract**

16   Virtual Reality (VR) and derived technologies which mixes the real world with some aspect of

17   virtuality (e.g., Augmented Reality, Mixed Reality) has emerged as a powerful allied in

18   education. Recent technological advances made Virtual and Mixed Reality (VMR) accessible

19   at our fingertips. However, only recently VMR has been explored for the teaching of Biology.

20   In this review, we describe how VMR applications are useful in Biology education, discuss the

21   caveats related to VMR use that can interfere with learning, and look into the future of VMR

22   applications in the field. We then propose a conceptual model for the future of VMR in

23   Biology, which envisage to combine VMR with Machine Learning and Artificial Intelligence

24   to provide unprecedented ways to visualise how species evolve in self-sustained immersive

25   virtual worlds, thereby transforming VMR from an educational tool to the centre of biological

26   interest. This conceptual paper aims to stimulate debates on how new technologies can

27   revolutionise teaching and learning across scenarios, which can be useful for improving

28   learning outcomes of biological concepts in face-to-face, blended, and distance learning

29   programmes.

30

31   **Keywords** : Darwinian theory ; new technology ; evolutionary biology ; immersive reality ;

32   evolving algorithm

Introduction

With increasing computational power, technologies that were costly or impossible to implement in the past have now become accessible in laptops and mobile phones (Kish 2004; Waldrop 2016). These technologies are now revolutionising the ways we interact with the world, how we learn, and how we teach (Veletsianos 2010). Virtual and Mixed Reality (VMR, see Box 1 for terminology) is one of these technologies which has gained increasing attention in the academic and teaching communities (Mazuryk and Gervautz 1996). In fact, over the last decade, there has been an exponential increase in the publication of papers in topics involving Virtual and Mixed Reality in Education (Fig 1a). VMR can be defined as an alternate world filled with computer-generated entities that interact with human sensory and motor systems to cause a sense of 'presence' (psychological state) in the subject through the use of an 'immersive' technology (i.e., technology that simulates an environment that is not necessarily real) (Yoh 2001). Presence can be defined as 'a state of dissociation from reality in which people feel the subjective experience of existing in the digital environment (Slater 2003).' Although presence and immersion have been used interchangeably (Barbot and Kaufman 2020), experiences that increase presence do not necessarily increase immersive feelings, and vice versa [see meta-analysis by (Cummings and Bailenson 2016)], suggesting that, although these terms refer to the feeling of 'being there', they are not necessarily equivalent. Nevertheless, both are important in VMR applications. According to the Oxford dictionary, Virtual Reality is defined as 'images and sounds created by a computer that seem almost real to the user, who can interact with them by using sensors', which highlights that presence and immersion are key aspects of virtual reality [see e.g., (Lombart et al. 2020)]. According to Milgram et al. (1995)'s taxonomy, immersive experiences are achieved through a complex continuum in reproduction fidelity of both the real and virtual environments, whereby the limitations of approaches as well as hardware (e.g., devices and displays) can influence the degree of immersive experience and presence available to the user (Milgram et al. 1995). Note, however, that the feeling of presence and immersion may not necessarily be the ultimate goal of VMR technologies [(Milgram et al. 1995); but see (Sheridan 1992; Robinett 1992)], although the increasingly more realistic displays can eventually result in one feeling complete immersion and presence (Naimark 1991).

VMR has been around for decades, and it thought to have its origin when, in the 1960s, Morton Heilig created one of the first immersive multi-sensory simulator that included stimuli such as sound, scent, wind and vibration (called 'Sensorama') (Heilig 1962; Mazuryk and Gervautz

67   1996). Ever since, VR technology has advanced significantly to the point that today there exists

68   many platforms for creating as well as experiencing VMR applications [e.g., (Ledermann and

69   Schmalstieg 2005; Jerald et al. 2014; Wexelblat 2014)]. In the last decade, the use of VMR in

70   teaching and learning has increased dramatically, and spans across a variety of subjects

71   (Hoffman and Vu 1997; Mikropoulos and Natsis 2011; Davies, Crohn, and Treadgold 2019;

72   Makransky, Thisgaard, and Gadegaard 2016), including biology (Makransky et al., 2016; Shim

73   et al., 2003; Shim, Kim, & Park, 2000). A meta-analysis of sixteen studies has shown that VMR

74   surgical simulators decrease the time to complete surgical procedures, suggesting a more

75   efficient surgical skill acquisition (Haque and Srinivasan 2006). Furthermore, VMR improves

76   the learning of tasks that require spatial and visual memory, observation, as well as control of

77   emotional responses in stressful conditions (Jensen and Konradsen 2018). Importantly, autistic

78   children have been described as having positive engagement with VMR applications in

79   educational settings (Strickland et al. 1996; Kandalaft et al. 2013), suggesting that VMR can

80   be used in a wide range of contexts and function as an inclusive tool for the education of

81   students with special needs. Therefore, VMR has the potential to become an important

82   educational tool in our century (Hoffman and Vu 1997).

83

84   In this conceptual paper, we first provide a mini-review of VMR applications that are changing

85   teaching and learning in biology. Next, we discuss the potential caveats associated with

86   misuses of VMR applications and discuss how VMR use can hinder (rather than help) teaching

87   and learning. We believe this balanced view is important to guide future developments in the

88   field. Lastly, we look into the future of VMR technology and discuss the directions in which

89   VMR developments can take us, revolutionising teaching of important principles of nature. We

90   propose a conceptual model of how VMR can act as an independent, self-sustained virtual

91   experimental world (which we call 'BioVR'). For brevity, we use a broad definition of VMR

92   which includes all virtual types of applications, from Augmented Reality (AR), Mixed Reality

93   (MR) through to Virtual Reality *sensu stricto* (see Box 1). This paper's main objectives are to

94   provide a balanced overview of the costs and benefits of using VMR into the classroom for

95   teaching evolutionary biology concepts and stimulate discussion about the future of

96   educational technology by proposing a conceptual innovative application of VMR (what we

97   called 'BioVR') in the classroom for an effective teaching of evolutionary biology that can

98   encapsulate three domains of learning (i.e., cognitive, affective, and psychomotor). It is equally

99   important to mention that this paper does not aim to provide a step-by-step guideline for the

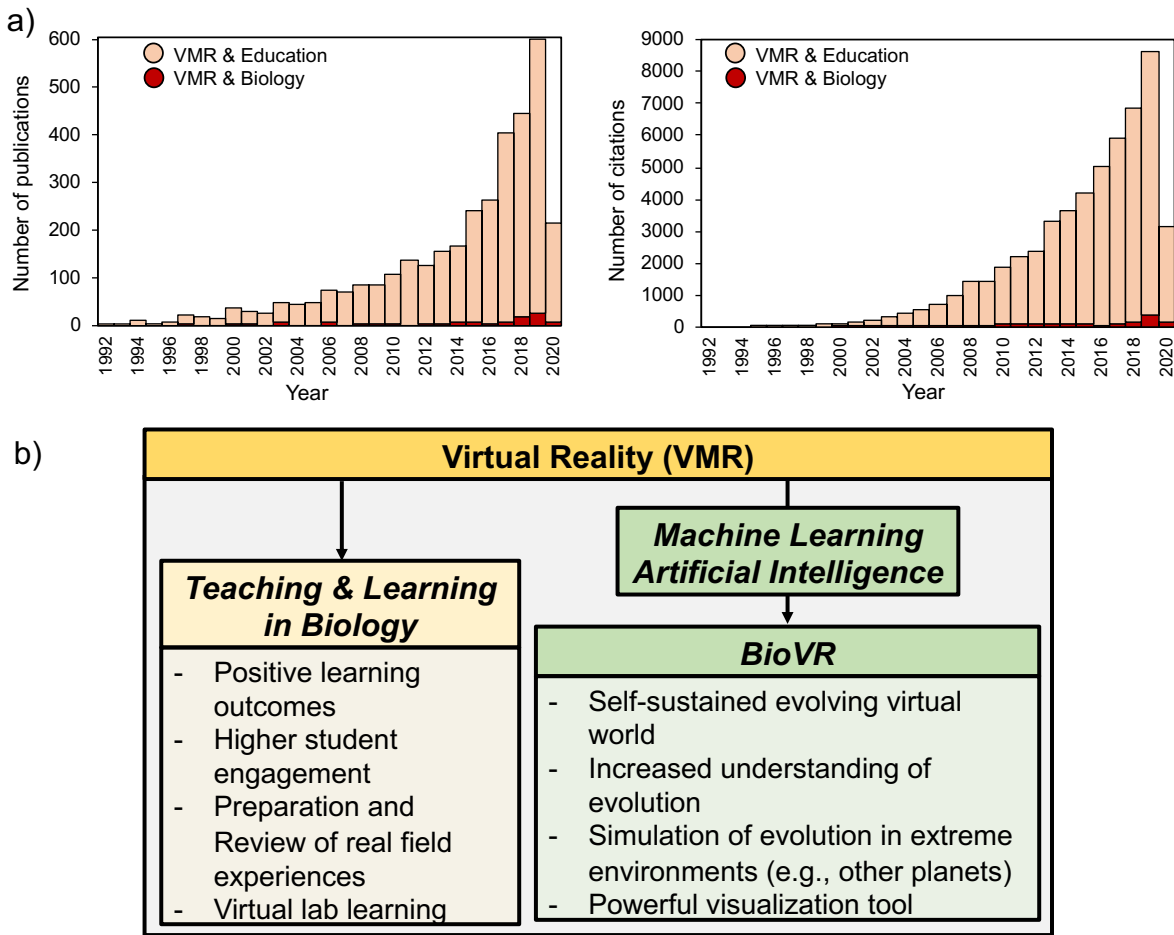
100 implementation of VMRs in the classroom, as these guidelines are available elsewhere (see our

101   discussions below). Having defined the scope of this conceptual paper, we hope that this paper

102   will help guide future developments in VMR applied to biology in a constructive manner,

103   stimulating collaborations across fields (e.g., Computer Science and Gaming) to develop new

104   teaching technologies to facilitate and enhance students' learning experiences.

105

106   **Fig 1 – VMR increasing importance in academic and educational context.** (a) Web of

107   Science Topic query of publications (left) and citations (right) that involves VMR and

108   education (orange) and VMR and biology (red). WoS searches were conducted on 12-May-

109   2020 with search term queries '(virtual AND augmented) reality AND education' or '(virtual

110   AND augmented) reality AND biology'. For each search, reviews and proceedings of

111   conferences were excluded. In total, there were 6,443 and 133 papers that fitted the selection

112   criteria, respectively. (b) Schematic overview of the potential for VMR to impact Biology. On

113   one hand, VMR has increasingly been used for teaching of a variety of topics within Biology.

114   As technology advances, it may be possible to combine other cutting-edge technologies such

115   as Machine Learning and Artificial Intelligent to create a self-sustained evolving virtual world

116   (BioVR) that allows us to gain insights into biological processes.

117

VMR uses in Biology education

119   While VMR in education has gained exponential attention of the academic community, VMR

120   in biology has advanced at a slower pace, comprising ~ 5% of academic publications in the

121   field (Fig 1a). Nonetheless, VMR has gained important applications in both secondary and

122   tertiary education biology courses (Makransky, Thisgaard, and Gadegaard 2016; Poland,

123   Baggott la Velle, and Nichol 2003; de Jong, Linn, and Zacharia 2013; Thisgaard and

124   Makransky 2017). A number of VMR applications attempt to reproduce the laboratory

125   environment to students with otherwise no access to laboratory facilities, with demonstrated

126   benefits over traditional lectures [see e.g., Labster (Bonde et al. 2014)]. Other VMR

127   applications were designed to give the students an immersive experience of more specific

128   biological processes such as cell structure (McClean, Slator, and White 1999), spatial

129   orientation (Moritz and Meyer 2004), and vision formation in animals (Gochman et al. 2019).

130   Students report higher engagement and learning outcomes with immersive experiences offered

131   by VMR applications, which is encouraging for the use of VMR in biology education

132   (Makransky, Terkildsen, & Mayer, 2019; Makransky et al., 2016; Mikropoulos, Katsikis,

133   Nikolou, & Tsakalis, 2003; Mikropoulos & Natsis, 2011; Shim et al., 2003) (Fig 1b). For

134   example, Moritz and Meyer (2004) designed an immersive interactive VMR platform for

135   visualisation and teaching of conformation and geometry of protein crystallographic structures,

136   whereby the test group was able to identify characteristics and regions in the samples that were

137   obfuscated in non-immersive programs (Moritz and Meyer 2004). Thus, innovative curricula

138   that harness the power of new technologies can provide significant benefits to the teaching and

139   learning of biology (Eastwood and Sadler 2013; Sadler et al. 2015).

140

141   VMR applications could help learning and teaching of ecology by simulating field expeditions

142   in which students have to identify plants and/or animals in virtual reality, as in non-immersive

143   virtual field trips developed previously [e.g., (Spicer and Stratford 2001; Dunleavy, Dede, and

144   Mitchell 2009)]. Students have in fact reported that non-immersive virtual field trips provide a

145   useful complement to the real field trip and could be a powerful tool to prepare and revise real

146   field trips (Spicer and Stratford 2001). This could also complement units of taxonomy of plants

147   and animals as well as provide virtual field experience to the student prior to the real task,

148   thereby amalgamating students' learning experience. In VMR, immersive scenarios could

149   include representative environments from different ecosystems (e.g., Amazon rainforest,

150   tundra, desert) in which the aim is to identify the greater number of plant species as well as the

151   morphological traits that are shared amongst species.

152

153   It is important to mention that virtual systems have been developed to explore all aspects of

154   biology education. For instance, pervious digital material has been designed for teaching and

155   learning of astrobiology [for instance in the *Habitable Worlds* platform (Horodyskyj et al.

156   2018)], although not yet in the fully immersive platform of VMR. *Habitable Worlds* allows

157   students to experience a inquiry-driven learning environment designed to enhance students'

158   learning outcomes on science through observation and modelling of virtual systems

159   (Horodyskyj et al. 2018). The results are promising as more than 70% of students had grades

160   average or higher, and student engagement significantly increased compared to benchmark. As

161   such, *Habitable Worlds* provides some guidelines for the design of digital platforms that could

162   be transferable to VMR systems, including automated feedback tailored to the students' needs

163   and student-educator interactions (both in real-time and in forums) (Horodyskyj et al. 2018). It

164   will be interesting for future developments of *Habitable Worlds* to expand the educational

165   content from astrobiology to other subjects within biology, as well as to include VMR

166   experience and compare the performance of students with traditional *versus* immersive

167   platforms.

168

169   **The potential misuses of VMR**

170   As for any new technology, we are still discovering the limitations of VMR applications as

171   educational tools. VMR applications are attractive because they contain a wide variety of

172   sensory stimuli that give the participant a sense of presence. However, too many stimuli – such

173   as colours, shapes, characters, movement – can distract the participant and have detrimental

174   effects on learning, a phenomenon that has been acknowledged in the literature and commonly

175   referred to as *cognitive overload* (Whitelock et al. 2000). A recent study has shown that

176   university students learned less and experienced higher cognitive overload when they

177   experienced a science lab in a fully-mounted VMR headset as oppose to the VMR scenes

178   played on 2D displays, in spite of higher feeling of presence in the VMR scene as opposed to

179   the 2D screen display (Makransky, Terkildsen, and Mayer 2019). This suggests that, in some

180   cases, the very same attributes that make VMR attractive can make VMR applications

181   ineffective. Nonetheless, it is possible to mitigate cognitive overload by controlling the

182   information flow that students are exposed to as part of the design of the environment, the tasks

183   needed to be completed, as well as the degree of interactivity with the environment at any given

184   point in time [e.g., (Dorneich et al. 2003; Wang et al. 2019; Andersen et al. 2016; Bharathan et

185   al. 2013)]. Other potential negative effects of VMR applications are motion sickness and

186   dizziness caused by the immersive experience, which can preclude appropriate understanding

187   of the learning material and hamper students' achievement of learning outcomes (McCauley

188   and Sharkey 1992; Regan and Price 1994; Ohyama et al. 2007; Davis, Nesbitt, and Nalivaiko

189   2015; Palmisano, Mursic, and Kim 2017). For instance, the perception of angular and linear

190   accelerations cause intense motion sickness both in short and long exposure to VMR

191   applications (McCauley and Sharkey 1992; LaViola Jr 2000; Saredakis et al. 2020; Sharples et

192   al. 2008). Yet, recent studies have demonstrated that motion-sickness can be mitigated or

193   eliminated through appropriate use of VMR design (e.g., immersiveness of the application)

194   and suitable hardware (e.g., display type) [see e.g., (Mittelstaedt, Wacker, and Stelling 2018;

195   Mittelstaedt, Wacker, and Stelling 2019; Weech, Kenny, and Barnett-Cowan 2019)].

196   Interestingly, a recent meta-analysis suggested that the feelings of presence and motion-

197   sickness likely trade-off – with higher presence resulting in lower motion-sickness (Weech,

198   Kenny, and Barnett-Cowan 2019), supporting the idea that motion-sickness can be mitigated

199   (or eliminated) with thoughtful design and user-experience.

200

201   Recent literature provides comprehensive lists of fundamental characteristics of 3D virtual

202   environments and general features that can be adjusted to increase students' engagement and

203   learning in virtual systems [see e.g., (Dalgarno and Lee 2010; Lindgren et al. 2016; O'Connor

204   and Domingo 2017)]. In fact, a series of learning affordances have been identified, which we

205   reproduce in Table 1, that have positive influence on students' engagement with virtual

206   applications and can ultimately enhance learning (Dalgarno and Lee 2010); these learning

207   affordances are revisited in our BioVR model (see below). These affordances highlight the

208   benefits of using VMR applications in the classroom. Here, our point is to reiterate the

209   importance of careful design and testing of new VMR applications prior to implementation in

210   the classroom in order to mitigate potential cognitive overload and/or motion sickness, which

211   could significantly hamper VMR's educational potential and the achievement of learning

212   affordances (Dalgarno and Lee 2010). Future studies will provide more detailed evidence-

213   based guidelines to build effective VMR applications that maximise educational potential

214   while minimising negative effects of VMR misuse (Dunleavy, Dede, and Mitchell 2009;

215   Akçayır and Akçayır 2017).

216

217   **Bio-inspired systems and the rise of artificial evolution**

218 The parallels between natural and artificial evolutionary systems have long been recognised
219 and explored. While few artificial life systems exist, perhaps the most famous example comes
220 from the work of Thomas Ray and the 'Tierra' system (Langton 1986; Langton 1997; Lehman,
221 Clune, and Misevic 2018; Ray 1992). The Tierra system simulates artificial life in self-
222 replicating, evolving entities ('algorithms') confined within virtual computer spaces, whereby
223 the entities can be considered as uni- or multi-cellular entities that experience errors in
224 replication analogous to mutations in biological reproduction (Ray 1992; Thearling and Ray
225 1994; Ray 1994). Instead of solar energy and natural resources as in biological systems,
226 artificial entities compete for central processing unit (CPU) and memory space [analogous to
227 energy and spatial resource, respectively [as described in (Ray 1992)]. As a result, artificial
228 Tierra entities become progressively more adapted to exploit one another in order to gain
229 advantage over the use of CPU and memory (Ray 1992; Thearling and Ray 1994; Ray 1994;
230 Ray and Xu 2001). The outcome of this self-sustained virtual evolutionary world is remarkable
231 given that the system evolves differences in entity sizes, ecological specialisation (e.g.,
232 parasites) and population dynamics processes (e.g., extinction) (Ray, 1992, 1994; Ray & Xu,
233 2001; Shao & Ray, 2010). This provides an unprecedented study case to compare and
234 understand how different shapes and forms emerge through evolutionary processes. However,
235 visualisation of evolution in the Tierra system is not straightforward and largely inaccessible
236 to a broader audience due to the highly technical language underlying the system. This poses a
237 significant barrier to biologists with limited computational expertise and it is, to some extent,
238 visually unappealing for students of biological sciences and related disciplines. Consequently,
239 it is difficult (though not impossible) to use artificial model systems such as Tierra as an
240 effective educational tool in the classroom while keeping the attention span and interest of
241 students.

242

243 **Can VMR and Artificial Intelligence (AI) revolutionise artificial evolutionary systems?**
244 As discussed above, VMR is a powerful and appealing educational technology to teach
245 biology. This is because students and educators respond rationally as well as emotionally to
246 the educational material in the immersive experience, which can accentuate learning (de Jong,
247 Linn, and Zacharia 2013; Thisgaard and Makransky 2017; Dunleavy, Dede, and Mitchell 2009;
248 Harley et al. 2016; Riva et al. 2007). Thus, VMR can be an appropriate way to overcome
249 accessibility problems of artificially evolving systems while increasing visual appealing to
250 specialists and general audience.

251

252   The technological advances that allowed VMR to become an accessible tool has also allowed
253   for the feasibility of powerful statistical models of Machine Learning and Artificial Intelligence
254   (AI). Machine Learning are algorithms that process and learn with huge amounts of data in
255   order to perform a task without necessarily being explicitly programmed to do so (Bishop
256   2006). AI attempts to simulate human intelligence in machine systems; this includes machine
257   learning but also (bio-inspired) robotics, ethics and philosophy associated with AI development
258   (Russell and Norvig 2002). Importantly, AI advances have recently demonstrated that
259   machines can learn from data beyond human capabilities (Chouard 2016; Gibney 2016).
260   Furthermore, a new area on the interface between VMR and AI aims to integrate AI to entities
261   in VMR (Luck and Aylett 2000; Laukkanen et al. 2004; Augusto et al. 2013). As a result, a key
262   question emerges: can we combine Machine Learning and AI with VMR to create a self-
263   sustained evolving virtual world (a 'BioVR')? If so, why should we combine VMR with AI?
264   The answer to the first question is, in our opinion, a sounding 'yes'. We strongly believe that
265   future technological advances have the potential to create an immersive virtual world that
266   reproduces the forces of evolution, which can allow us to visualise and measure how species
267   have evolved, how ecosystems are formed, how species adapt to their environment, how we
268   can anticipate effects of adverse climatic conditions across ecosystems in our changing world.
269   In a sense, we could become 'virtual naturalists' that explore evolution in a simulated (virtual)
270   world in the same sense that naturalists explore the natural (real) world. The learning benefits
271   are unprecedented given that students can experience inaccessible and inhospitable
272   environments, observe evolution, adaptation, trophic interaction, parasitism and many more
273   biological processes without stepping outside the classroom (Learning affordance #2; Table 1).
274   Moreover, the freedom given to the students within these BioVRs forms the perfect ground for
275   inquiry-based learning and engagement, where the students will observe and explore the
276   environment, measuring and experiencing the virtual environment to inquiry about the
277   underlying virtual biological phenomena (Horodyskyj et al. 2018) (Learning affordance # 3,
278   Table 1). Ultimately, the BioVR could be used to supplement and stimulate collaborative
279   learning tasks, where students may compare and contrast the evolution of individual BioVR
280   evolutions and identify similarities (e.g., parallel evolution) and divergences (e.g.,
281   specialisation traits) between virtual entities (Learning affordance #5; Table 1). The BioVR
282   could then eliminate the need for complex computational expertise (at least from the users'
283   point of view) and provide a fully immersive, artificial world upon which entities evolve
284   following basic principles of biological evolution in our and other planets, while students can
285   explore the environment and learn from their own virtual experience.

286

287   Practical implementation of BioVR by experts could in theory be achieved through the

288   following steps:

1. Simulate an artificial 'planet' whereby entities will interact, compete, and evolve. In this artificial planet, the 'biotic' rules are established, such as the basic environmental conditions (e.g., temperature), habitat (e.g., marine vs terrestrial landscapes), resource distribution and so on [similar in concept to the 'soup' in Tierra and the concept of virtual environments in (Luck and Aylett 2000)].

2. Design the ancestor entity, defining the rules of reproduction, mutation, and ecological interactions that govern the outcomes of interactions between entities as well as with the environment in the planet. This will likely require that the entities follow theoretical models that relate trait expression and fitness, as well as fitness changes over lifetime and through generations [see for example models in (Edelaar and Bolnick 2019)]. We envisage that the ancestor entity is the 'building block' for artificial life to evolve in BioVR and without it, the system does not have the evolving entity. The ancestor entity is equivalent to the ancestor species which gave origin to life on Earth, and is a common feature of artificial life systems [e.g., (Ray 1994)]. In other words, the ancestral entity is the first 'living' inhabitant of the virtual planet.

3. Gather a large empirical dataset of environment–traits–species interactions as a basic starting-point for determining how different species evolve in different ecosystems (e.g., evolutionary convergences, divergences, character displacement) – this could be called 'rules of evolution'. This will allow the system to 'know' which adaptations are more likely to yield fitness advantages in a given environment. For instance, heat tolerance (or traits related to coping with high temperatures) is a likely to increase fitness of populations living in virtual habitats that resemble arid regions. The actual evolution of traits following the 'rule of evolution' will depend on the variability present in the ancestral entity populations and we envisage that, in a BioVR simulation, this parameter can adjustable according to the purpose or the needs of the virtual world. One way in which evolutionary rules could be extracted from this dataset is using, for example, supervised learning and/or clustering algorithms (see Box 2) to extract general rules as to how species evolve (morphologically and behaviourally) across different environments, commonality between functional traits across species in the same environments, as well as the number, distribution, and behaviour of different species within the same environment. For instance, species living in warm habitats are likely

320 to share similar adaptations to high temperatures and thus, one could expect that virtual
321 entities inhabiting warm virtual habitats should resemble follow similar patterns. Once
322 these rules of evolution are estimated (or guessed) across all habitats of the virtual
323 world, ancestral entities can evolve and differentiate accordingly.

324 4. Ideally, BioVRs are self-sustained, and thus it would be interesting to have the changes
325 and adaptations in one time point to feedback into the system for the next time point.
326 For example, imagine that a species evolves a remarkable adaptation to convert virtual
327 resource A into B. This transformation should feedback into the system so as to allow
328 new evolutionary rules, perhaps favouring other species to adapt and utilise virtual
329 resource B (which is being produced) instead of virtual resource A (Fig 2).

330 5. Given this self-sustained cycle of interaction between entities and the environments,
331 and the iterative system that modulates virtual evolutionary rules, BioVR can become
332 an artificial ecosystem, fully accessible for exploration through VMR in inquiry-based
333 learning quests. This allows students and researchers to experience and study evolution
334 in this immersive environment, comparing the outcomes of evolutionary forces within
335 different environments within a BioVR and across BioVRs with different setups.
336 Furthermore, since data visualisation is key for understanding biological processes
337 [e.g., (Karr and Brady 2000)] and is an essential component of affective learning, the
338 use of VR to create BioVR worlds will allow VR to transcend the status of an
339 educational tool that helps learning and teaching in Biology to become the main
340 technology for experiencing and learning about virtual biological phenomena.

341

342 We provided these steps in order to quick-start ideas around the practical challenges necessary
343 to realise the conceptual proposition made in this paper. We are not presumptuous of our
344 knowledge boundaries and understand that experts may have better implementation methods
345 and other tools that we are unaware. Having said that, these steps are aimed to foster open
346 discussions that can generate international collaborations which may make possible for BioVR
347 to reach the classroom as an effective educational tool of the future. It is important to mention
348 that while the idea of BioVRs may seem now allusive, attempts to merge the fields of VMR,
349 artificial life, and AI have been around for decades (Luck and Aylett 2000), with more recent
350 efforts emerging from the astonishing 'boost' in computer power of our generation (Petrović
351 2018; Zhang et al. 2018). We are also aware that virtual environments, AI and semi-
352 autonomous VMR agents have been developed for other purposes such as direct or assist users
353 into tasks [see e.g., (Luck and Aylett 2000)]. To our knowledge, concepts similar to the one of

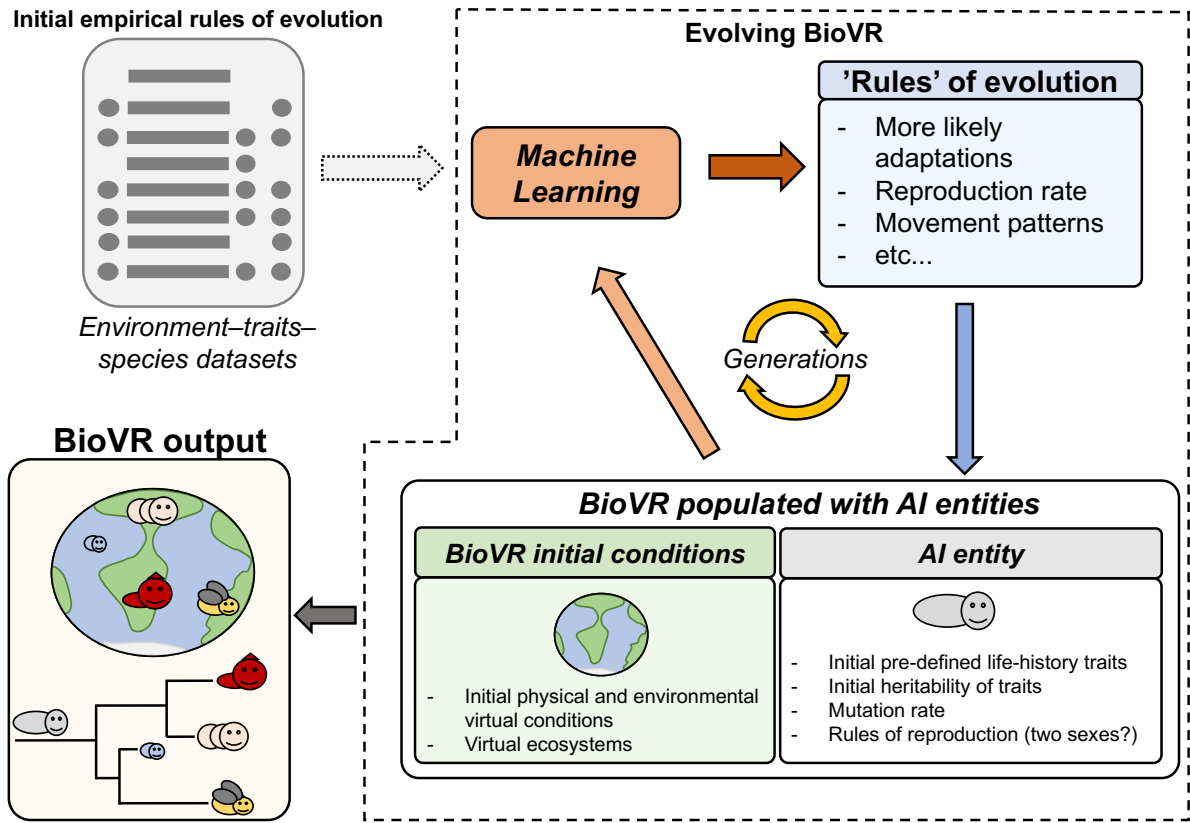
354 BioVR as presented in this paper have never been conceptualised let alone tested, which

355 underscores the importance of opening this avenue of communication around the concept of

356 BioVR for future developments that aid education of Biology. Future research and discussion

357 should therefore aim at assessing the feasibility of the concepts proposed here.

358

359

360 **Fig 2 –Conceptual overview of the steps to build a BioVR.** A supervised machine learning

361 algorithm is implemented to empirical environment-trait-species datasets in order to extract the

362 patterns (or 'rules') of evolution across environments. Meanwhile, the initial settings for the

363 BioVR world and the ancestral AI entity are also set. The settings include physical and

364 environmental conditions, as well as patterns of lifespan, movement, and reproduction of the

365 AI entity. Next, the 'rules of evolution' are incorporated into the BioVR and AI entity with

366 original settings, and the BioVR is allowed to evolve. Note that the evolution patterns in the

367 BioVR are then fed-back to the machine learning model, which is updated. This way, the only

368 input from empirical data is at the initial states, and BioVR are allowed to evolve independently

369 afterwards. As a result, we can measure and visualise species evolution as it happens, in an

370 immersive experience of the BioVR.

371

372

373   **Conclusion**

374   The use of VMR has provided promising results for consolidating learning across secondary

375   and tertiary biology education. With increasing technology, the combination of VMR with

376   Machine Learning and AI has the potential to create a self-sustained evolving virtual world

377   (BioVR) that allow us to uniquely explore how life as we know evolves and responds to

378   extreme climatic conditions. Thus, the use of new technologies and innovative applications can

379   provide better learning outcomes and student experiences in face-to-face, blended, and distance

380   learning contexts by amalgamating biological principles in immersive classrooms.

381

382   **Funding details**

383   This study was not funded by any funding agency.

384

385   **Conflict of interest**

386   The authors have no conflict of interests to declare.

387   **References**

388   Akçayır, Murat, and Gökçe Akçayır. 2017. "Advantages and Challenges Associated with
389   Augmented Reality for Education: A Systematic Review of the Literature." *Educational*
390   *Research Review* 20: 1–11. doi:https://doi.org/10.1016/j.edurev.2016.11.002.
391   Andersen, Steven Arild Wuyts, Peter Trier Mikkelsen, Lars Konge, Per Cayé-Thomasen, and
392   Mads Sølvsten Sørensen. 2016. "The Effect of Implementing Cognitive Load Theory-
393   Based Design Principles in Virtual Reality Simulation Training of Surgical Skills: A
394   Randomized Controlled Trial." *Advances in Simulation* 1 (1). Springer: 20.
395   Augusto, Juan C, Vic Callaghan, Diane Cook, Achilles Kameas, and Ichiro Satoh. 2013.
396   "'Intelligent Environments: A Manifesto.'" *Human-Centric Computing and Information*
397   *Sciences* 3 (1): 12. doi:10.1186/2192-1962-3-12.
398   Barbot, Baptiste, and James C Kaufman. 2020. "What Makes Immersive Virtual Reality the
399   Ultimate Empathy Machine? Discerning the Underlying Mechanisms of Change."
400   *Computers in Human Behavior*. Elsevier, 106431.
401   Bharathan, Rasiah, Saaliha Vali, Thomas Setchell, Tariq Miskry, Ara Darzi, and Rajesh
402   Aggarwal. 2013. "Psychomotor Skills and Cognitive Load Training on a Virtual Reality
403   Laparoscopic Simulator for Tubal Surgery Is Effective." *European Journal of Obstetrics*
404   *& Gynecology and Reproductive Biology* 169 (2). Elsevier: 347–352.
405   Bishop, Christopher M. 2006. *Pattern Recognition and Machine Learning*. Edited by M
406   Jordan, J. Kleinberg, and B. Scholkopf. Cambridge, UK: Springer Science Business
407   Media.
408   Bonde, Mads T, Guido Makransky, Jakob Wandall, Mette V Larsen, Mikkel Morsing, Hanne
409   Jarmer, and Morten O A Sommer. 2014. "Improving Biotech Education through
410   Gamified Laboratory Simulations." *Nature Biotechnology* 32 (7): 694–697.
411   doi:10.1038/nbt.2955.
412   Chouard, Tanguy. 2016. "The Go Files: AI Computer Wraps up 4–1 Victory against Human
413   Champion." *Nature News*.
414   Cummings, James J, and Jeremy N Bailenson. 2016. "How Immersive Is Enough? A Meta-
415   Analysis of the Effect of Immersive Technology on User Presence." *Media Psychology*

416   19 (2). Taylor & Francis: 272–309.

417   Dalgarno, Barney, and Mark J W Lee. 2010. "What Are the Learning Affordances of 3-D
418   Virtual Environments?" *British Journal of Educational Technology* 41 (1). John Wiley
419   & Sons, Ltd: 10–32. doi:10.1111/j.1467-8535.2009.01038.x.

420   Davies, Andrew Graham, Nick J Crohn, and Laura Anne Treadgold. 2019. "Can Virtual
421   Reality Really Be Used within the Lecture Theatre?" *BMJ Simulation and Technology
422   Enhanced Learning* 5 (4): 234 LP – 235. doi:10.1136/bmjstel-2017-000295.

423   Davis, Simon, Keith Nesbitt, and Eugene Nalivaiko. 2015. "Comparing the Onset of
424   Cybersickness Using the Oculus Rift and Two Virtual Roller Coasters." In *Proceedings
425   of the 11th Australasian Conference on Interactive Entertainment (IE 2015)*, 27:30.

426   de Jong, Ton, Marcia C Linn, and Zacharias C Zacharia. 2013. "Physical and Virtual
427   Laboratories in Science and Engineering Education." *Science* 340 (6130): 305 LP – 308.
428   doi:10.1126/science.1230579.

429   Dorneich, Michael C, Stephen D Whitlow, Patricia May Ververs, and William H Rogers.
430   2003. "Mitigating Cognitive Bottlenecks via an Augmented Cognition Adaptive
431   System." In *SMC'03 Conference Proceedings. 2003 IEEE International Conference on
432   Systems, Man and Cybernetics. Conference Theme-System Security and Assurance (Cat.
433   No. 03CH37483)*, 1:937–944. IEEE.

434   Dunleavy, Matt, Chris Dede, and Rebecca Mitchell. 2009. "Affordances and Limitations of
435   Immersive Participatory Augmented Reality Simulations for Teaching and Learning."
436   *Journal of Science Education and Technology* 18 (1): 7–22. doi:10.1007/s10956-008-
437   9119-1.

438   Eastwood, Jennifer L, and Troy D Sadler. 2013. "Teachers' Implementation of a Game-
439   Based Biotechnology Curriculum." *Computers & Education* 66: 11–24.
440   doi:https://doi.org/10.1016/j.compedu.2013.02.003.

441   Edelaar, Pim, and Daniel I Bolnick. 2019. "Appreciating the Multiple Processes Increasing
442   Individual or Population Fitness." *Trends in Ecology & Evolution* 34 (5). Elsevier: 435–
443   446.

444   Gibney, Elizabeth. 2016. "Google AI Algorithm Masters Ancient Game of Go." *Nature News*
445   529 (7587): 445.

446   Gochman, Samuel R, Marilyn Morano Lord, Naman Goyal, Kristie Chow, Benjamin K
447   Cooper, Lauren K Gray, Stephanie X Guo, et al. 2019. "Tarsier Goggles: A Virtual
448   Reality Tool for Experiencing the Optics of a Dark-Adapted Primate Visual System."
449   *Evolution: Education and Outreach* 12 (1): 9. doi:10.1186/s12052-019-0101-6.

450   Haque, S, and S Srinivasan. 2006. "A Meta-Analysis of the Training Effectiveness of Virtual
451   Reality Surgical Simulators." *IEEE Transactions on Information Technology in
452   Biomedicine* 10 (1): 51–58. doi:10.1109/TITB.2005.855529.

453   Harley, Jason M, Eric G Poitras, Amanda Jarrell, Melissa C Duffy, and Susanne P Lajoie.
454   2016. "Comparing Virtual and Location-Based Augmented Reality Mobile Learning:
455   Emotions and Learning Outcomes." *Educational Technology Research and
456   Development* 64 (3): 359–388. doi:10.1007/s11423-015-9420-7.

457   Heilig, Morton L. 1962. "Sensorama Simulator." Google Patents.

458   Hoffman, H, and D Vu. 1997. "Virtual Reality: Teaching Tool of the Twenty-First Century?"
459   *Academic Medicine : Journal of the Association of American Medical Colleges* 72 (12).
460   University of California, San Diego, School of Medicine, La Jolla, USA.
461   hhoffman@ucsd.edu: 1076–1081. doi:10.1097/00001888-199712000-00018.

462   Horodyskyj, Lev B, Chris Mead, Zack Belinson, Sanlyn Buxner, Steven Semken, and Ariel D
463   Anbar. 2018. "Habitable Worlds: Delivering on the Promises of Online Education."
464   *Astrobiology* 18 (1). Mary Ann Liebert, Inc., publishers: 86–99.
465   doi:10.1089/ast.2016.1550.

Jensen, Lasse, and Flemming Konradsen. 2018. "A Review of the Use of Virtual Reality Head-Mounted Displays in Education and Training." *Education and Information Technologies* 23 (4). Springer: 1515–1529.

Jerald, Jason, Peter Giokaris, Danny Woodall, Arno Hartbolt, Anish Chandak, and Sebastien Kuntz. 2014. "Developing Virtual Reality Applications with Unity." In *2014 IEEE Virtual Reality (VR)*, 1–3. IEEE.

Kandalaft, Michelle R, Nyaz Didehbani, Daniel C Krawczyk, Tandra T Allen, and Sandra B Chapman. 2013. "Virtual Reality Social Cognition Training for Young Adults with High-Functioning Autism." *Journal of Autism and Developmental Disorders* 43 (1). Springer: 34–44.

Karr, Timothy L, and Rachael Brady. 2000. "Virtual Biology in the CAVE." *Trends in Genetics* 16 (5). Elsevier: 231–232. doi:10.1016/S0168-9525(00)01996-X.

Kish, L B. 2004. "Moore's Law and the Energy Requirement of Computing versus Performance." *IEE Proceedings - Circuits, Devices and Systems* 151 (2): 190–194. doi:10.1049/ip-cds:20040434.

Langton, Christopher G. 1986. "Studying Artificial Life with Cellular Automata." *Physica D: Nonlinear Phenomena* 22 (1): 120–149. doi:https://doi.org/10.1016/0167-2789(86)90237-X.

Langton, Christopher G. 1997. *Artificial Life: An Overview*. Mit Press.

Laukkanen, Seppo, Ilkka Karanta, Ville Kotovirta, Jussi Markkanen, and Jukka Rönkkö. 2004. "Adding Intelligence to Virtual Reality." In *Proceedings of the 16th European Conference on Artificial Intelligence*, 1136–1141. Citeseer.

LaViola Jr, Joseph J. 2000. "A Discussion of Cybersickness in Virtual Environments." *ACM Sigchi Bulletin* 32 (1). ACM New York, NY, USA: 47–56.

Ledermann, Florian, and Dieter Schmalstieg. 2005. *APRIL: A High-Level Framework for Creating Augmented Reality Presentations*. IEEE.

Lehman, Joel, Jeff Clune, and Dusan Misevic. 2018. "The Surprising Creativity of Digital Evolution." In *Artificial Life Conference Proceedings*, 55–56. MIT Press.

Lindgren, Robb, Michael Tscholl, Shuai Wang, and Emily Johnson. 2016. "Enhancing Learning and Engagement through Embodied Interaction within a Mixed Reality Simulation." *Computers & Education* 95: 174–187. doi:https://doi.org/10.1016/j.compedu.2016.01.001.

Lombart, Cindy, Elena Millan, Jean-Marie Normand, Adrien Verhulst, Blandine Labbé-Pinlon, and Guillaume Moreau. 2020. "Effects of Physical, Non-Immersive Virtual, and Immersive Virtual Store Environments on Consumers' Perceptions and Purchase Behavior." *Computers in Human Behavior*. Elsevier, 106374.

Luck, Michael, and Ruth Aylett. 2000. "Applying Artificial Intelligence to Virtual Reality: Intelligent Virtual Environments." *Applied Artificial Intelligence* 14 (1). Taylor & Francis: 3–32. doi:10.1080/088395100117142.

Makransky, Guido, Thomas S Terkildsen, and Richard E Mayer. 2019. "Adding Immersive Virtual Reality to a Science Lab Simulation Causes More Presence but Less Learning." *Learning and Instruction* 60. Elsevier: 225–236.

Makransky, Guido, Malene Warming Thisgaard, and Helen Gadegaard. 2016. "Virtual Simulations as Preparation for Lab Exercises: Assessing Learning of Key Laboratory Skills in Microbiology and Improvement of Essential Non-Cognitive Skills." *PLOS ONE* 11 (6). Public Library of Science: e0155895. https://doi.org/10.1371/journal.pone.0155895.

Mazuryk, Tomasz, and Michael Gervautz. 1996. "Virtual Reality-History, Applications, Technology and Future." Citeseer.

McCauley, Michael E, and Thomas J Sharkey. 1992. "Cybersickness: Perception of Self-

Motion in Virtual Environments." *Presence: Teleoperators and Virtual Environments* 1 (3). MIT Press: 311–318. doi:10.1162/pres.1992.1.3.311.

McClean, Phillip E, Brian M Slator, and Alan R White. 1999. "The Virtual Cell: An Interactive, Virtual Environment for Cell Biology." In *EdMedia+ Innovate Learning*, 1442–1443. Association for the Advancement of Computing in Education (AACE).

Mikropoulos, Tassos A, Apostolos Katsikis, Eugenia Nikolou, and Panayiotis Tsakalis. 2003. "Virtual Environments in Biology Teaching." *Journal of Biological Education* 37 (4). Routledge: 176–181. doi:10.1080/00219266.2003.9655879.

Mikropoulos, Tassos A, and Antonis Natsis. 2011. "Educational Virtual Environments: A Ten-Year Review of Empirical Research (1999–2009)." *Computers & Education* 56 (3): 769–780. doi:https://doi.org/10.1016/j.compedu.2010.10.020.

Milgram, Paul, Haruo Takemura, Akira Utsumi, and Fumio Kishino. 1995. "Augmented Reality: A Class of Displays on the Reality-Virtuality Continuum." In *Proc.SPIE*. Vol. 2351. doi:10.1117/12.197321.

Mitchell, R S, J G Michalski, and T M Carbonell. 2013. *An Artificial Intelligence Approach*. Berlin, Germany: Springer,.

Mittelstaedt, Justin Maximilian, Jan Wacker, and Dirk Stelling. 2019. "VR Aftereffect and the Relation of Cybersickness and Cognitive Performance." *Virtual Reality* 23 (2). Springer: 143–154.

Mittelstaedt, Justin, Jan Wacker, and Dirk Stelling. 2018. "Effects of Display Type and Motion Control on Cybersickness in a Virtual Bike Simulator." *Displays* 51. Elsevier: 43–50.

Moritz, E, and J Meyer. 2004. "Interactive 3D Protein Structure Visualization Using Virtual Reality." In *Proceedings. Fourth IEEE Symposium on Bioinformatics and Bioengineering*, 503–507. doi:10.1109/BIBE.2004.1317384.

Naimark, Michael. 1991. "Elements of Real-Space Imaging: A Proposed Taxonomy." In *Stereoscopic Displays and Applications II*, 1457:169–179. International Society for Optics and Photonics.

O'Connor, Eileen A, and Jelia Domingo. 2017. "A Practical Guide, with Theoretical Underpinnings, for Creating Effective Virtual Reality Learning Environments." *Journal of Educational Technology Systems* 45 (3). SAGE Publications Sage CA: Los Angeles, CA: 343–364.

Ohyama, Seizo, Suetaka Nishiike, Hiroshi Watanabe, Katsunori Matsuoka, Hironori Akizuki, Noriaki Takeda, and Tamotsu Harada. 2007. "Autonomic Responses during Motion Sickness Induced by Virtual Reality." *Auris Nasus Larynx* 34 (3): 303–306. doi:https://doi.org/10.1016/j.anl.2007.01.002.

Palmisano, Stephen, Rebecca Mursic, and Juno Kim. 2017. "Vection and Cybersickness Generated by Head-and-Display Motion in the Oculus Rift." *Displays* 46. Elsevier: 1–8.

Petrović, V M. 2018. "Artificial Intelligence and Virtual Worlds – Toward Human-Level AI Agents." *IEEE Access* 6: 39976–39988. doi:10.1109/ACCESS.2018.2855970.

Poland, Roger, Linda Baggott la Velle, and Jon Nichol. 2003. "The Virtual Field Station (VFS): Using a Virtual Reality Environment for Ecological Fieldwork in A-Level Biological Studies—Case Study 3." *British Journal of Educational Technology* 34 (2). John Wiley & Sons, Ltd: 215–231. doi:10.1111/1467-8535.00321.

Ray, Thomas S. 1992. *Evolution, Ecology and Optimization of Digital Organisms*. Citeseer.

Ray, Thomas S. 1994. "Evolution, Complexity, Entropy and Artificial Reality." *Physica D: Nonlinear Phenomena* 75 (1): 239–263. doi:https://doi.org/10.1016/0167-2789(94)90286-0.

Ray, Thomas S, and Chenmei Xu. 2001. "Measures of Evolvability in Tierra." *Artificial Life and Robotics* 5 (4): 211–214. doi:10.1007/BF02481504.

566   Regan, E C, and K R Price. 1994. "The Frequency of Occurrence and Severity of Side-
567   Effects of Immersion Virtual Reality." *Aviation, Space, and Environmental Medicine*.
568   Aerospace Medical Assn.
569   Riva, Giuseppe, Fabrizia Mantovani, Claret Samantha Capideville, Alessandra Preziosa,
570   Francesca Morganti, Daniela Villani, Andrea Gaggioli, Cristina Botella, and Mariano
571   Alcañiz. 2007. "Affective Interactions Using Virtual Reality: The Link between
572   Presence and Emotions." *CyberPsychology & Behavior* 10 (1). Mary Ann Liebert, Inc. 2
573   Madison Avenue Larchmont, NY 10538 USA: 45–56.
574   Robinett, Warren. 1992. "Synthetic Experience: A Proposed Taxonomy." *Presence:*
575   *Teleoperators & Virtual Environments* 1 (2). MIT Press: 229–247.
576   Russell, Stuart, and Peter Norvig. 2002. *Artificial Intelligence: A Modern Approach*. Upper
577   Saddle River New Jersey: Pearson Education.
578   Sadler, TROY D, WILLIAM L Romine, DEEPIKA Menon, RICHARD E Ferdig, and
579   LEONARD Annetta. 2015. "Learning Biology Through Innovative Curricula: A
580   Comparison of Game- and Nongame-Based Approaches." *Science Education* 99 (4).
581   John Wiley & Sons, Ltd: 696–720. doi:10.1002/sce.21171.
582   Saredakis, Dimitrios, Ancret Szpak, Brandon Birckhead, Hannah A D Keage, Albert Rizzo,
583   and Tobias Loetscher. 2020. "Factors Associated with Virtual Reality Sickness in Head-
584   Mounted Displays: A Systematic Review and Meta-Analysis." *Frontiers in Human*
585   *Neuroscience* 14. Frontiers Media SA.
586   Serino, Maeve, Kyla Cordrey, Laura McLaughlin, and Ruth L Milanaik. 2016. "Pokémon Go
587   and Augmented Virtual Reality Games: A Cautionary Commentary for Parents and
588   Pediatricians." *Current Opinion in Pediatrics* 28 (5). Wolters Kluwer: 673–677.
589   Shao, Jie, and Thomas S Ray. 2010. "Maintenance of Species Diversity by Predation in the
590   Tierra System." In *ALife*, 533–540.
591   Sharples, Sarah, Sue Cobb, Amanda Moody, and John R Wilson. 2008. "Virtual Reality
592   Induced Symptoms and Effects (VRISE): Comparison of Head Mounted Display
593   (HMD), Desktop and Projection Display Systems." *Displays* 29 (2). Elsevier: 58–69.
594   Sheridan, Thomas B. 1992. "Musings on Telepresence and Virtual Presence." *Presence:*
595   *Teleoperators & Virtual Environments* 1 (1). MIT Press: 120–126.
596   Shim, K C, H S Kim, and Y C Park. 2000. *Application of Multi-Media in Biology Education,*
597   *Summer Program of Korean Society of Biology Education*. Edited by null. Vol. null.
598   Null.
599   Shim, Kew-Cheol, Jong-Seok Park, Hyun-Sup Kim, Jae-Hyun Kim, Young-Chul Park, and
600   Hai-Il Ryu. 2003. "Application of Virtual Reality Technology in Biology Education."
601   *Journal of Biological Education* 37 (2). Routledge: 71–74.
602   doi:10.1080/00219266.2003.9655854.
603   Slater, Mel. 2003. "A Note on Presence Terminology." *Presence Connect* 3 (3). Citeseer: 1–
604   5.
605   Spicer, John, and J Stratford. 2001. "Student Perceptions of a Virtual Field Trip to Replace a
606   Real Field Trip." *Journal of Computer Assisted Learning* 17 (December): 345–354.
607   doi:10.1046/j.0266-4909.2001.00191.x.
608   Strickland, Dorothy, Lee M Marcus, Gary B Mesibov, and Kerry Hogan. 1996. "Brief
609   Report: Two Case Studies Using Virtual Reality as a Learning Tool for Autistic
610   Children." *Journal of Autism and Developmental Disorders* 26 (6). Springer: 651–659.
611   Thearling, Kurt, and Thomas S Ray. 1994. "Evolving Multi-Cellular Artificial Life." In
612   *Artificial Life IV*, 283–288.
613   Thisgaard, Malene, and Guido Makransky. 2017. "Virtual Learning Simulations in High
614   School: Effects on Cognitive and Non-Cognitive Outcomes and Implications on the
615   Development of STEM Academic and Career Choice ." *Frontiers in Psychology* .

https://www.frontiersin.org/article/10.3389/fpsyg.2017.00805.

Veletsianos, George. 2010. *Emerging Technologies in Distance Education*. Athabasca University Press.

Waldrop, M Mitchell. 2016. "The Chips Are down for Moore's Law." *Nature News* 530 (7589): 144.

Wang, Danding, Qian Yang, Ashraf Abdul, and Brian Y Lim. 2019. "Designing Theory-Driven User-Centric Explainable AI." In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, 1–15.

Weech, Séamas, Sophie Kenny, and Michael Barnett-Cowan. 2019. "Presence and Cybersickness in Virtual Reality Are Negatively Related: A Review ." *Frontiers in Psychology* . https://www.frontiersin.org/article/10.3389/fpsyg.2019.00158.

Wexelblat, Alan. 2014. *Virtual Reality: Applications and Explorations*. Academic Press.

Whitelock, Denise, Daniela Romano, Anne Jelfs, and Paul Brna. 2000. "Perfect Presence: What Does This Mean for the Design of Virtual Learning Environments?" *Education and Information Technologies* 5 (4). Springer: 277–289.

Yoh, Myeung-Sook. 2001. "The Reality of Virtual Reality." In *Proceedings of the Seventh International Conference on Virtual Systems and Multimedia (VSMM'01)*, 666. VSMM '01. USA: IEEE Computer Society.

Zhang, Z, B Cao, J Guo, D Weng, Y Liu, and Y Wang. 2018. "Inverse Virtual Reality: Intelligence-Driven Mutually Mirrored World." In *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, 735–736. doi:10.1109/VR.2018.8446260.

Zhu, Xiaojin, and Andrew B Goldberg. 2009. "Introduction to Semi-Supervised Learning." *Synthesis Lectures on Artificial Intelligence and Machine Learning* 3 (1). Morgan & Claypool Publishers: 1–130.

Zsila, Ágnes, Gábor Orosz, Beáta Bőthe, István Tóth-Király, Orsolya Király, Mark Griffiths, and Zsolt Demetrovics. 2018. "An Empirical Study on the Motivations Underlying Augmented Reality Games: The Case of Pokémon Go during and after Pokémon Fever." *Personality and Individual Differences* 133: 56–66. doi:https://doi.org/10.1016/j.paid.2017.06.024.

647   **Box 1 – The reality-virtuality continuum**

648   In a highly influential paper, Milgram, Takemura, Utsumi, & Kishino (1995) proposed the

649   reality-virtuality continuum (see Fig 3) to classify Virtual, Augmented, and Mixed reality

650   technologies. On one side of the spectrum is the real world (reality) and, on the other side of

651   the spectrum, the fully virtual world (virtuality) where Virtual Reality (VR) in its strict sense

652   resides. In between the extremes, stands Augmented Reality (AR) – which relies mostly on

653   real world elements but with the addition of virtual entities; the best known (and controversial)

654   example of AR has been Pokemon Go! (Serino et al. 2016; Zsila et al. 2018) – and Augmented

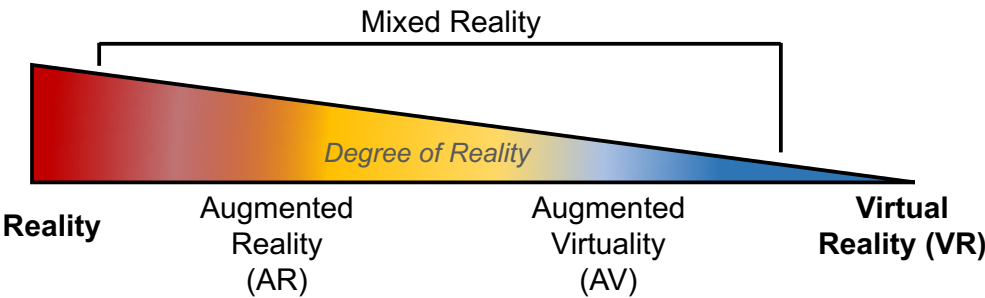
655   Virtuality (AV) with the opposite of AR, that is, mostly virtual world but with the addition of

656   'real' entities. AR and AV are cases of Mixed Reality (MR), where real and virtual elements

657   are intertwined within the application (see Fig 3). For the purpose of this paper and for

658   simplicity, we refer to AR, AV, and VR all as *virtual and mixed reality* (VMR) applications

659   because they all have some degree of virtual components introduced into the application.

660

661   **Fig 3 – The reality-virtuality continuum.** AR – augmented reality; AV – augmented

662   virtuality; VR – virtual reality (based on Milgram et al., 1995).

663

664

665

666

667

668

669

670

671

672

673

674

675 **Box 2 – Supervised and unsupervised machine learning.**

676 Machine learning models can be broadly classified into *supervised* or *unsupervised* learning

677 algorithms, depending on the structure of the data (Mitchell, Michalski, and Carbonell 2013)

678 (Note: there are intermediate cases called *semi-supervised learning* which we will not consider

679 here, see e.g., (Zhu and Goldberg 2009) for details). Unsupervised learning algorithms use data

680 in which the outcome is not yet labelled or identified, and therefore the algorithm cannot

681 'know' the outcomes in advance. The algorithm then learns how to classify and predict the

682 outcome from new observations based on the inherent structure of the data at hand. An example

683 of unsupervised learning is the clustering of groups within a dataset (Fig 4a). Conversely,

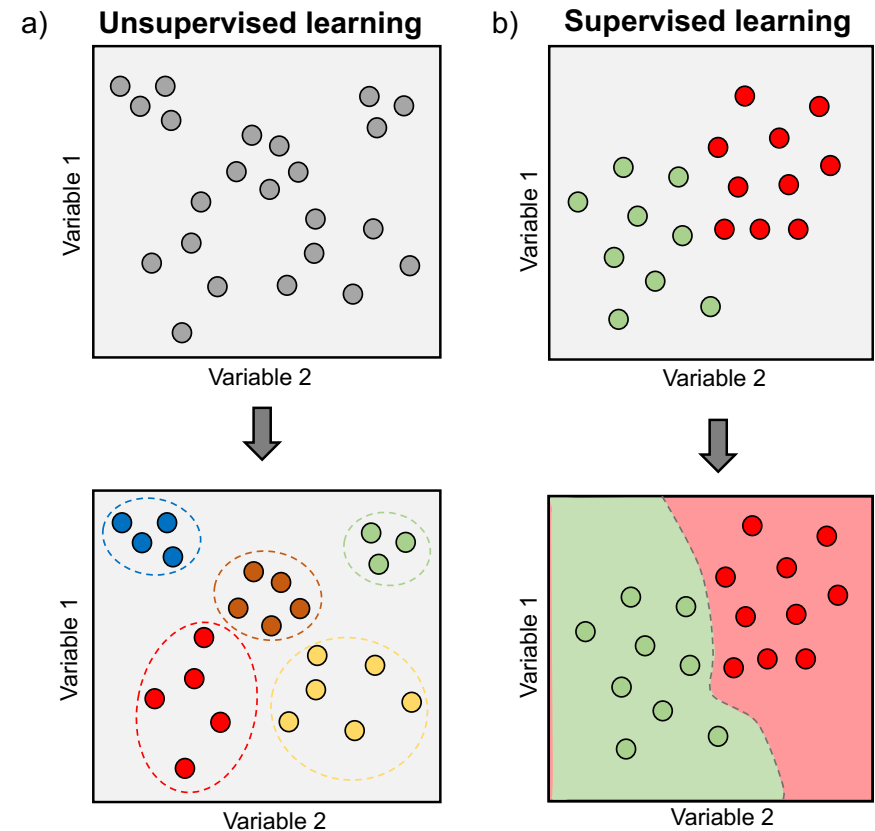
684 supervised learning algorithms uses data in which the outcome is known, and the algorithm

685 learns how to predict the outcome of future observations based on what was learnt from the

686 information and outcomes obtained from previous data. An example of supervised learning is

687 the classification (or prediction, in the case of regression models) of a new observation between

688 two categories based on *n* number of characteristics or variables (Fig 4b).

689

690 **Fig 4– Supervised and unsupervised machine learning.** a) Schematic representation of an

691 unsupervised learning model. Unlabelled data is used in unsupervised learning algorithms for

692   clustering. b) Schematic representation of a supervised learning model. Labelled data are used

693   in supervised learning algorithms for classification.

694