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Entangled cognition in immersive learning experience

Claudio Aguayo[1,5,6,7], Ronnie Videla-Reyes[2,5,6,7,8] and Tomas Veloz[3,4,5,6,7]

Abstract

Immersive learning environments in education provide a set of rich and diverse learning affordances (possibilities). Cognition in such environments can be considered as embodied, enacted, embedded, and extended (the 4Es of cognition). During such cognitive happenings, we assume and live as valid everything we experience. Yet in this enactive structural coupling between individuals and their experiential world, another phenomenon occurs. We become a behaviorally inseparable entity with the virtual/immersive world. We become entangled with that virtual/immersive world. Here we propose that, within the framework of the 4Es of cognition, a recognizable lived experience phenomena occurs when learners engage with virtual or immersive learning environments. That is, cognition becomes entangled in immersive environments with alternative realities. Coming from the Santiago school of cognition, and building from ideas from immersive learning, 4E cognition, and quantum entanglement inspired in quantum cognition, we attempt to describe the process of entangled cognition happening in immersive learning environments. We recognize at least two levels of entanglement from the same recursive phenomenology: one we call a local entanglement, related to perception and sense-making; and a second we call a global entanglement, connected to the process and phenomena of human consciousness and meaning-making, accessible when conceived as a whole. We see the benefits for such a theoretical framework to ultimately guide, justify, and encourage the emergence of an epistemology shift in educational technology towards design principles that account for entangled cognition in immersive learning (and beyond), and the associated possibilities offered by new immersive technologies in education.

Keywords

Enaction, entanglement, immersive learning, mixed reality, 4E cognition, Santiago school, quantum cognition

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1. Introduction

> Lo notable en todo esto es que para la realización de nuestro vivir-convivir humano no importa lo que creemos o no creemos, lo fantástico o lo no-fantástico o irreal que vivimos, porque vivimos como válido todo lo que vivimos en el momento de vivirlo: si pensamos y aceptamos que vivimos algo fantástico o irreal, vivimos algo fantástico o irreal, si pensamos que lo que vivimos no es fantástico, aunque otros piensen que lo es, lo que vivimos no lo vivimos como fantástico e irreal.
>
> *[What is remarkable in all this is that for the realization of our human living-coexistence it does not matter what we believe or do not believe, the fantastic or the non-fantastic or unreal that we live, because we live as valid everything that we live at the moment of living it: if we think and accept that we live*

[1]AppLab, Te Ara Poutama, Faculty of Māori and Indigenous Development, Auckland University of Technology, New Zealand
[2]Escuela de Educación Diferencial, Facultad de Educación, Universidad Santo Tomás, Chile
[3]Departamento de Matemáticas, Universidad Tecnológica Metropolitana, Chile
[4]Centre Leo Apostel for Interdisciplinary Studies, Vrije Universiteit Brussel, Belgium
[5]Buckminster College, Brussels, Belgium
[6]Foundation for the Interdisciplinary Development of Science, Technology and Arts, Chile
[7]Innovasteam Lab, La Serena, Chile
[8]Escuela de Educación, Universidad Católica del Norte, Chile

Corresponding author:
Claudio Aguayo, Auckland University of Technology Faculty of Māori and Indigenous Development, 55 Wellesley St East, Auckland, 1142, New Zealand.
Email: claudio.aguayo@aut.ac.nz

something fantastic or unreal, we live something fantastic or unreal, if we think that what we live is not fantastic, although others think it is, what we live we do not experience as fantastic and unreal.]

(Maturana & Dávila, 2015, p. 334).

In the opening quote above, Maturana and Dávila (2015) allude to an important concept we use here as a starting point to introduce the notion of quantum entanglement in/during our cognitive happenings in/within our world; and how immersive learning environments offer an opportunity to contemplate this phenomenon. The notion that during the realization of our human living-coexistence we assume and "live as valid everything that we live at the moment of living it" (p. 334), *regardless of its nature and whether we believe it or not*, touches on a remarkable phenomenon recognizable when people engage with immersive technology experiences and affordances (possibilities offered by digital tools and systems). The bodily cognition reality enacted by a user/learner in an immersive environment makes them "to become" with the newly encountered virtual/immersive reality world, living it as valid at the moment of living it.

This cognitive phenomenon of "living as real," whether it is part of our real personal/sub-personal natural world, or a fantastic, unreal, virtual, and/or artificial living to us, leads us to consider the changes in our perception when we switch from one reality to another; and how does that relate to the current 4E cognition framework of human experience (Gallagher, 2017; Thompson, 2007). We turn to quantum physics and the concept of entanglement, as if human cognition could manifest itself as entangled with different synchronic and superimposed reality threads and states as they present themselves, whether in real life or virtually. What we entangle with becomes part of our human living-coexistence in the world, whatever the nature of that world is. This has led us to explore the idea of entangled cognition in immersive and virtual environments from a 4E cognition and quantum physics epistemology. We do so by seeing some resemblance between the structural characteristics of the learning process and the configuration of meaning that homologates, in some aspects, with what has been understood about what happens in the microscopic world when quantum physics was first created.

Penrose (1994) argues that the foundations of quantum theory for the study of consciousness are based on overcoming dualisms: subject/object, body/mind, organism/environment. These foundations are consistent with the principles of the 4Es of cognition: embodied, enactive, embedded, and extended. This can be complemented by considering quantum entanglement as a process of intermingling between the observer over the observed, as fundamental to represent the correlation between the way of making sense and the substrate in which the experience occurs (virtual and/or real). It is even possible to conjecture the collapse of states induced by the change of perspective when switching from one reality to another, and the current state that the organism lives in once it is (re-)coupled.

These ideas and concepts coming from quantum theory can be related to enactivism and the other approaches of the 4E framework of cognition. Enactivism is rooted in the notion of autonomous systems generating their own worlds from their actions (Maturana & Varela, 1984). Unlike cognitivist approaches that consider cognition reduced to internal computational processes translated into representations of the environment, enactive approaches place emphasis on the action of perception to grasp the world (Hutto & Myin, 2013). We ask ourselves, then, from the enactive approaches, about how cognitive agents comprehend their perceived reality when transitioning within or between real and/or virtual immersive environments? An understanding of this entanglement phenomenon occurring within human cognition can help to examine immersive user experience from 4E cognition in the light of quantum theory, while linking digital immersion and sensorimotor theory of cognition and learning. This is of importance in the theorization of human experience in immersive learning environments. An understanding of such human experience can in turn guide the design of immersive learning experiences in education, while providing unique targeted opportunities for the action of perception through dynamic user-environment structural coupling (Aguayo, 2021).

Coming from the epistemology of the Santiago school of cognition (Maturana & Varela, 1980), here we elaborate on some similarities and commonalities found in quantum theory, particularly in its application as a formal framework for modeling reasoning and semantic processes, known as quantum cognition (Aerts, 2009; Veloz, 2015; Wang et al., 2013). We do so, firstly, to highlight the existence of a recognizable cognitive phenomenon understood from the lens of quantum cognition, which we call here the "quantum footprint"; and secondly, as a source of epistemological inspiration and development to address immersive learning experience research, design, and practice, within the framework of 4E cognition applied in education. We propose framing human experience with sensorimotor lived reality in the real world and in immersive/virtual learning environments as a process resembling the dynamics of a quantum system.

We conceive this process as a process of adaptation/collapse and entanglement in the superposition of available states of reality between the observer and the observed. We see this entanglement process underlying the process of enaction, by means of progressive and complex multisensorial coordination occurring in the adaptation to the newly encountered reality. We conceptualize this on the notion of structural coupling, where the switch between cognitive experiences can be regarded as a process of re-coupling and co-construction of reality through the collapse and entanglement between the observer and the newly observed experience. By doing so, we connect epistemological ideas from quantum theory applied within the domain of human cognition and semantics to conceptualizing the structural coupling between the learner and the learned as a behavior of adaptation, or collapse of states, and entanglement.

To illustrate this cognitive entanglement when users/learners switch from their natural real world situation to an immersive/virtual reality (VR) world, consider the two VR experience examples shown in Figure 1. On the left side, we see a virtual simulation of a high-altitude mountaineering scenario (part of an in-house mountain safety education VR app, see Hong (2019)); and on the right side, we can see the Mission: International Space Station (ISS) game,[1] depicting the interior of the ISS users can explore and navigate (available in the Meta Quest Store[2]). In both cases, once users/learners put on their VR headsets and engage with the experience presented, regardless of the real life situation (e.g., at home, in a classroom, summertime, etc.), they immediately "adapt" cognitively and bodily to the new scenario. In this "switch" from one reality to another, the new lived experience becomes valid for the user/learner during its duration, whether it is experiencing a high-altitude storm white-out and early signs of mountain sickness, or a zero-gravity feeling while floating around the ISS.

From our theoretical lens, we can conceive the human experience for both realities, be it the real world and the immersive/virtual world, from the framework of 4E cognition. Alluding to embodied cognition, we can say that when we are with VR headsets and devices, our behavior constitutively depends on our corporality. In turn, our phenomenology of living a world as real or virtual, whether feeling a strong storm or floating in the space of the metaverse, depends on how the organism makes sense of environmental encounters that maximize or inhibit behavior. From enactivism, we share the belief, supported by Rolla et al. (2022), that immersive and VR devices, along with other technological and digital learning affordances, have the potential to provide limitless experiences. This continuous interplay between our dynamic sensorimotor interactions and the contingencies of the lived experience, contribute to an ongoing process of sense-making. We can ride a motorcycle for the first time or manipulate digital objects using VR controllers, and feel frustrated at not displaying effective behaviors, because we have not adapted a coordinated set of actions according to the environmental feedback of the task. Therefore, we sense making in the flow of contingent actions, whether real or virtual, as a product of our experiences.

Likewise, and within the framework of embedded cognition, VR devices are progressively integrated and incorporated into the agent-tool coupling dynamics, transforming the state of situationality and the significant possibilities of action with materiality. For example, see a group of students frustrated with a science text trying to learn the process of mitotic and meiotic cell division in 2D, until they can see it virtually in 3D and/or augmented reality (AR). These 3D digital modalities expand the learning affordances as they actively explore the environment,

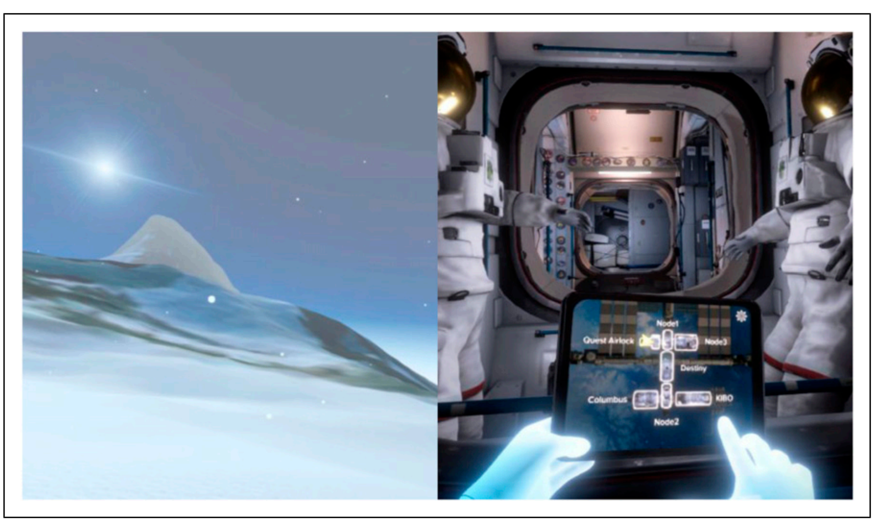

Figure 1. Examples of virtual immersive learning environments where users/learners can experience cognitive entanglements between their real world situation, and the newly encountered virtual world reality when they switch between real and virtual realities. Left side: a mountain safety education VR app where users can learn to deal with high-altitude high-risk situations (image copyright: AUT AppLab). Right side: the Mission: ISS game from Magnopus, available for Meta Quest2 VR headset, where users can experience a feeling of zero gravity while moving around the International Space Station or taking spacewalks (image copyright: Meta Quest).

through changes in perception generating new opportunities for action. In the case of extended cognition, it occurs either within the available artifacts in the real world we extend our cognition to, or through new immersive technologies, such as VR headsets, smartphones, or AR displays allowing us to experience immersive/virtual worlds.

Educational researchers committed to embodied approaches to cognition, reveal research designs that feed on sensorimotor theories of learning, for example: perceptual multimodality (Radford, 2010); ecological dynamics (Abrahamson & Sánchez-García, 2016) and 4E cognition applied to make technologies of 3D manufacturing and creative electronics (Videla & Veloz, 2023). However, regarding the development of new and emerging learning technologies such as AR, VR and mixed reality (MR/XR) technology, platforms, tools, systems, and affordances, serious attempts to comprise an immersive enactive approach to learning in these contexts are emergent. In this line, some studies that stand out include the effectiveness of immersive VR in higher STEM education (Pande et al., 2021); creation and analysis of immersive environments that are pedagogically structured to support situated and experiential education (Schott & Marshall, 2018); bridging art, science and technology in meaningful ways using XR (Jowsey & Aguayo, 2017); the use of XR for self-determined free-choice marine conservation education (Eames & Aguayo, 2019) and the effectiveness of full-immersion VR technology for experiential education (Schott & Marshall, 2020).

While the 4Es provide an explanatory framework for understanding how agent-tool sensorimotor engagement elicits experiences in the real and virtual worlds, we consider the process of switching from one reality to another, and vice versa, which has been incipiently addressed by the 4E approach. Willing to explore how the cognitive switch between different realities arises, we pose ourselves the following question: How does the switch from the natural real world to the immersive/virtual world, and vice versa, occur in the context of an immersive/VR learning experience? The 4E cognition approach, and enactivism in particular, can provide a comprehension of how users/learners live as valid their real and immersive/virtual worlds during the experience. But the process of switching between these two realities, and how the lived cognitive experience adapts to a new world from a previous one, is unclear.

From the 4E cognition approach, we explore quantum entanglement and quantum cognition, under the view that quantum physics epistemology does provide a relatable framework to address and understand the cognitive phenomena occurring when users/learners switch from one reality to the other, and vice versa. In this process, we adopt a systemic perspective approach of theoretical integration, incorporating elements from quantum theory and quantum cognition, perception phenomenology, and cognitive enactivism. We attempt to articulate quantum entanglement and quantum cognition with the 4E cognition approach, under the view that the process of structural re-coupling in the enactment of the new world encountered, whether real or virtual, is at the basis of the cognitive reality switch.

This framework offers a set of principles for the understanding of the enactment of human experience in immersive and virtual learning environments. It can guide, justify, and encourage design principles in immersive learning from an enactive approach that accommodates the entanglement of different cognitive realities. This could contribute to educational psychologists and educational technology researchers, designers, and practitioners exploring the possibilities offered by new immersive technologies in education.

2. 4E cognition, quantum entanglement, and the quantum cognition “footprint”

2.1. 4E cognition and human experience

“In finding the world as we do, we forget all we did to find it as such, entangled in the strange loop of our actions through our body” (Varela, 1984, p. 9). In the face of the representationalist and functionalist primacy of the cognitivist program ignoring the role of the body and the environment, the internalist explanations derived from processing and neurocentrism began to suffer tensions that gave way to the postcognitivist movement. This movement originates in the early 1990s with the emergence of the seminal book The Embodied Mind, which emphasizes the role of the experience of sense-making through: the enaction of Varela et al. (1991); the artifactual and distributed cognition that reveals the importance of the environment proposed in Cognition in the Wild by Hutchins (1995) and the extended functionalism that encompasses brain processing, body information, and environmental scaffolding in The Extended Mind by Clark and Chalmers (1998) (Newen et al., 2018).

From these ideas that initiated the postcognitivist research program, which is framed in the anti-representationalist, situated and embodied assumptions of cognition, the computational affinities for understanding the mind were put to an end. The postcognitivist program, plus the influences of ecological psychology and embodied cognition gave way to the 4E approach to cognition (embodied, enactive, embedded, and extended) which have argued in favor of active and embodied interaction of the agent in and with the environment. From this approach, cognition is intertwined with the world, given the action of direct perception and tacit knowledge in which organisms interact with objects in the environment long before they have the ability to abstract their characteristics (Chemero, 2011; Hutto & Myin, 2013; Thompson, 2007). The perception-cognition-action continuity reaffirms the ecology of causal circular interactions that contribute to preserving the meta-stability and identity of organisms (Fuchs, 2017).

The embodied cognition approach is based on the idea that cognitive abilities are constitutively dependent on bodily accomplishment. Merleau-Ponty (1962) introduces the notion of Motor Intentionality to develop the idea that our basic relationship with the world is distinctively embodied and non-intellectual in nature. The enactive approach from Varela et al. (1991) is framed in the theory of autopoiesis and cognition (Maturana & Varela, 1984), neurodynamics (Kelso, 1995), embodied cognition (Lakoff, 1988), and corporal phenomenology (Merleau-Ponty, 1962). This approach arises as a response to the Cartesian dualistic tradition that separates the mind and the body to account for the mental, and from which contemporary cognitivism is nourished reducing the world of meanings to mental representations (Hutto & Myin, 2013). The enactive approach provides a dynamic and complex understanding of the mental, establishing the continuous circulation between biological processes at the molecular level, sensorimotor coupling, and interactions with the environment (Thompson, 2007). The enaction construct emphasizes knowledge, far from being the representation of a pre-given world, but rather, the joint advent of a world and a mind from a history of structural couplings (Varela et al., 1991). Likewise, enactivism emphasizes the context dependence and the body as constitutive factors of cognition. In this sense, and as argued by Rojas-Líbano and Parada (2020), the historical contingencies of sensorimotor activities generate plastic changes within the organism, which in turn determine its capacities at a given moment that depends on the context for its effective coupling.

The extended approach to cognition refers to the extended functionalism that is nourished by sensory feedback from the body and the influences of the sociocultural environment. In particular, it is assumed that cognition must be understood beyond the skull and in relation to the artifacts of the environment (Ingold, 2011). Current approaches to extended cognition are based on the idea of brains as predictive machines for hierarchical processing and inferences (Clark, 2012). In the case of the embedded cognition approach, this refers to the capacity of the mind to be embedded in a sociocultural context. Here the works of Hutchins (1995) on distributed cognition through information patterns of the environment that allow behavior to be guided through material anchors are revealed (Hutchins, 2005). Thus, it also draws on the ecological approach to cognition, which assumes a structured environment of ecological information through affordances (Gibson, 1979) and social affordances (Rietveld & Kiverstein, 2014).

4E cognition approaches are based on the idea that cognition is something that organisms do, therefore, it is a dynamic activity embodied and extended in full resonance with environmental information (Hutto & Myin, 2013). Human beings as cognitive agents continually modify themselves by participating in sociomaterial environments that offer sustained and situated affordances of acting, thus establishing "control over the patterns that matter for the interactions that matter" (Clark, 2015, p. 5). In the case of the gradient of reality proposed by Milgram and Kishino (1994), it can be inferred from the 4E Cognition, that the experience is embodied in artifacts such as extensive and functional prostheses of thinking by doing in a continuum that goes from the real world to the virtual world and vice versa.

This strong functionalism in terms of Clark (2008) alludes to a bodily artifact intertwining in which the individual and the artifact progressively amalgamate a single unit. Think of the child who uses VR goggles with, for example, the MEL-VR mobile app to feel a particle of a gas in first-person and understand the kinetic motion of particles. At first, the child feels foreign to the VR glasses, they bother them, but at the same time it motivates them to persist in this mode of presence. Once it is coupled from the flow of sensorimotor contingencies (Di Paolo et al., 2017), which reveal the affective, motivational, and enactive commitment when experiencing the movement of a particle, the child is capable of reflecting and abstracting new relationships that arise from its own experience of being there among particles. This is "because affective responses support vision from the very moment visual stimulation begins" (Barrett & Bar, 2009, p. 1325).

The literature that links embodiment with immersive environments and virtual tools touches on fundamental aspects of this active commitment to be there, living the virtual as virtual and the real as real. However, there are some ascriptions with cognitivist remnants that place the role in the cognitive process and not in the experience. See Kilteni et al. (2012), who postulate the sense of corporeality as the "set of sensations that arise along with being inside, having and controlling a body" (p. 374). Likewise, they argue that "the body is a container in the context of VR" (p. 375). These authors try to answer the question of how and to what extent we can experience a virtual body representation as our own body within a virtual environment. This view points out that the sense of embodiment in VR contexts depends on three main components such as self-location, agency, and ownership of the body. In short, they explore the variety of self-representation of the body to the extent that they actively participate with the artifacts and account for "subjective experience of using and 'having' a body." (p. 373). In this way, they conclude that perceived agency is an important factor that gives coherence to the representation of the body itself and therefore, implies property.

Complementary to these ideas, and beyond an analytical approach, we argue against the dismantling of experience with technology. Rather, we argue for the complete experience or entanglement, where the body is not a container, but the basis of our being in the world (Merleau-Ponty, 1962). From this phenomenological perspective, we assume that "the body is established in each situation and unites us to the world by invisible threads of peculiar operative intentionality, threads that have already been formed in our first contacts with the world" (Merleau-Ponty, 1962, p. 74). Therefore, the body is not subtracted from situationality and its history of structural couplings. This reveals the ecological dimension, (see Bateson (1972)) in which the blind man, the stick, and the street denote a causal circularity, where it becomes impossible to determine the place occupied by the mind. Here, the "body schema is extended to incorporate the stick and, on the other hand, the brain treats the stick as if it were part of the body" (Ihde & Malafouris, 2019, p. 11). This indivisible human and tool, is consistent with radical enactivism approaches that hold that the basic forms of embodied cognition are dynamic processes that are anchored to the sociomaterial world that spans multiple temporal and spatial scales (Hutto & Myin, 2013).

If we analyze the initial experience with, for example, VR headsets, we notice that the body becomes transparent, but as it is coupled from the flow of sensorimotor contingencies, the body becomes invisible as we are entangled with the new reality that we live as such. We would say, in this case, this relates to the collapse or superposition of states. Our point here is, "we do not have a body, we are a body" (Nancy, 2003, p. 27). We argue that the body becomes visible and invisible in the dynamic flow of the situationality of those who live what they live, with or without artifacts, with or without technologies, given that it is not an additive aspect of cognition, but a constitutive one. The idea of the body as a container is restrictive in ecological and dynamic terms to refer to the embodiment of cognition with immersive environments such as VR.

Another relevant aspect in the line of studies with VR is the work of Makransky and Petersen (2021) who proposed the Cognitive Affective Model of Immersive Learning (CAMIL) to understand learning in immersive environments. The authors maintain that the "presence" or feeling of being there depends on the fidelity of representation of the environment in which one experiences what one experiences as real. Given that presence comes from perception, agency increases when interacting with VR headsets. However, the factors that best predict learning are affectivity, since they lead to a high perceived value and control of the agency that triggers greater enjoyment of the users. In fact, their ideas about experiencing a virtual self as the real self in a sensory or non-sensory way are given from the feeling of embodiment. On the other hand, the evidence of approaches from ecological psychology (Gibson, 1979) that are in tune with ideas of the 4E approach, show that the use of VR to favor immersive learning environments depends on five stages: representation of spatial knowledge, experiential learning, engagement, contextual learning, and collaborative learning (Dalgarno & Lee, 2010). These stages represent the evolution of fidelity to the virtual experience as an affective continuum that reorganizes the basic sense of self, which can be attributed to identity, the sense of presence, and co-presence when interacting with others.

Other studies on VR and cognition show indirect relationships between greater presence in virtual environments and low learning compared to REs (Makransky et al., 2019). In an exhaustive review of evidence on the design of virtual environments for immersive learning, the cognitive theory of multimedia learning (CTML) proposal accounts for some fundamental aspects: (i) effective learning does not require a high degree of immersion in most cases, but of immersive VR lessons in smaller units; (ii) the interactions must be directed by learning objectives, so that prior knowledge must be considered to favor the efficient construction of knowledge and (iii) the preparation of the students must occur both inside and outside of the immersive VR environment, as constructive learning activities must be embedded, inside or outside of the virtually designed world, for meaningful learning to occur (Mulders et al., 2020). Based on the evidence presented, we will show that there is no unified proposal on design principles that can incorporate foundations from 4E cognition and quantum cognition. Relevant approaches to VR, enactivism, and ecological psychology such as those by Rolla et al. (2022), are framed in epistemic and analytical questions that replace the notion of illusion with that of allusion when actively participating in virtual worlds. Even these reflections do not impact educational designers of virtual environments.

2.2. Quantum entanglement and the representation of wholeness in science

Entanglement is a quantum phenomenon that occurs when microscopic entities (particles, photons, atoms, etc.) interact in such a way that they become a behaviorally inseparable unit. The latter implies that, even though the entities can be separated in space (and time), it is impossible to describe them as a couple (or collection of) different entities (Horodecki et al., 2009). Indeed, the only meaningful description of the entities' system is in terms of a "global state" which encodes the properties of all the entangled entities, as if forming a global single entity.

This feature establishes an epistemological departure from the classical and reductionist approach to science because it embraces context dependence and wholeness as fundamental aspects of reality. Once entanglement was undoubtedly proven for microscopical systems, scientists started to test entanglement for larger systems (Vedral, 2008), and started harnessing the informational properties of entanglement in applications of diverse kind which led to what is known today as the second quantum revolution (Dowling & Milburn, 2003). Among them, we find quantum metrology, quantum computation and quantum cryptography.

In addition, researchers started identifying that quantum-like theoretical structures can also appear in cognitive situations such as of social systems (Wendt, 2015), processes of categorization (Aerts, 2009), decision-making (Busemeyer & Bruza, 2012), and semantic representation (Dalla Chiara et al., 2010; Surov et al., 2021), among others (Pothos & Busemeyer, 2022). These investigations instead of applying quantum theory to cognition at the biological level, proposed that quantum structures and mechanisms are in play at the information and meaning processing of cognitive phenomena. In particular, the mathematical formalism of quantum theory, involving particular forms for state representation, probability calculus, and time-evolution, can be extended to domains such as information retrieval, natural language processing, and automated-reasoning. Therefore, entanglement, as one of the core concepts of quantum theory, also possibly becomes a central feature of novel scientific approaches to traditional cognitive science (Pothos & Busemeyer, 2013).

There is an interesting structural relation between enactivism and quantum theory, and particularly with entanglement. While enactivism entails the co-creation of meaning from interaction between the observer and its environment, quantum theory postulates that the properties of a quantum system are acquired by it when it is observed (see the funny illustration of this concept by Schrodinger's cat in Hobson, 2018). Additionally, the structural coupling between the enactant and its environment implies that they become a whole, defying the traditional reductionist approach, similarly to how entanglement has defied the notion of particles in space, and later of compositional semantic entities in cognitive activities. For this reason, we believe that the formalism of quantum theory, which accounts for the collapse of system properties through observation and allows for non-compositional states that emerge from agent-environment interactions, can serve as a suitable framework to cognition for advancing digital and technological applications that seek to leverage the enactive aspects of learning.

It is important to clarify that quantum theory, as it departs from the traditional view of an objective reality to be found proposing the co-construction of reality through observation, has contradicted physicists since its very beginnings, and some profound philosophical debates about the nature of quantum entities remain unsolved (Friebe et al., 2018). The sides of this debate are called quantum interpretations (Görnitz & Weizsäcker, 1987), and propose ontological stands regarding the state (wave function), measurement (operator), and the nature of probabilities. It is out of the scope of this article to discuss the similarities and differences among different quantum interpretations. However, it is important to remark that not all quantum interpretations are equally compatible with enactivism. We consider that QBism (Fuchs et al., 2014) and the conceptuality interpretation (Aerts et al., 2020) that emerged from the quantum cognition approach, can be considered as philosophical starting points to explore the compatibility between enactive and quantum systems.

In particular, the conceptuality interpretation is a genuine realistic view, where quantum entities, and all reality in general, is considered to be of conceptual nature. Hence, there is more than a set of interaction rules, but a semantic-like interaction between the very constituents of our reality. In the same way that crowds can behave in coherent ways, quantum systems can behave as if there are fundamental rules, but these rules are the emergence of a more fundamental semantic-like process. Conceptual entities are seen as entities that can be in different states and be subjected to measurement processes, which are processes not only of discovery (of the properties that were already actual), but also of creation (of those properties that were only potential prior to the measurement and could become actual through its execution). In this way, the conceptuality interpretation can be applied not only at the micro-scale, but it might also appear in our context of everyday semantic experiences, and is the subject of investigation in quantum cognition (Veloz, 2015). Next, we explore quantum cognition and the notion of a quantum cognition "footprint."

2.3. Quantum structure in cognition

The integration of the quantum perspective in the analysis of entangled cognition in/within immersive learning environments through a 4E lens offers distinct insights and potential contributions. While it is acknowledged that the application of the 4E perspective itself is not entirely new, the incorporation of quantum theory provides additional layers of understanding. By integrating the quantum approach to cognition, we aim to go beyond the concept of entanglement and emphasize the underlying quantum concepts and processes that contribute to a quantum-like phenomena footprint in/within immersive learning experiences.

Representationalist approaches to cognition have encountered a number of obstacles due to how meaning is stored and processed following flexible structures. Interestingly, the same kind of obstacles were confronted by physicists when dealing with the mysterious behavior of microscopic entities in the early 20th Century, and stimulated the construction of quantum theory, whose ontological interpretation is up to now debated. It is important to mention that these obstacles do not appear in isolation, but form an interrelated mixture common to most cognitive phenomena. Hence, they present a difficult landscape for the development of formal theories of cognition. Without loss of generality, we will refer in general to "concepts" (i.e., abstract ideas) as the elements over which cognitive tasks such as perception, categorization, or decision-making, take place.

2.3.1. Gradeness, subjectivity, and vagueness. Concepts we reason with in our daily life are not sharply defined, neither in their boundaries nor in their implications (Rosch, 1973). For example, reasoning about the concept representing an objectual entity such as "pet." In this case, an instance such as "dog" is almost certainly categorized as a "pet" by anyone, but other instances such as "snake" or "robot" might not be unanimously categorized as a "pet." In the same way, we usually assume that a "bird" is "able to fly." However, the instance "penguin" is a "bird," but penguins do not fly. When we translate these questions to non-objectual concepts such as "freedom" or "love" the subjectivity of the instance-categorization task is even clearer. Cognitive psychologists have carried out a large number of experiments to reveal how people understand the meaning of concepts we use in daily life, and concluded the way people estimate the meaning of concepts cannot be modeled using binary systems ("yes"/"no"), but requires instead graded relations that reflect their structural vagueness (Zadeh, 1975). From here, we can use the notion of instance to explain the vagueness of this concept by assuming that concepts are represented by instances having different degrees of membership, typicality, similarity, and other "semantic estimations."

Note that instances can be considered as concepts on their own, inducing a hierarchical structure from abstract concepts instantiated by more concrete instances, which in turn are concepts instantiated by even more concrete instances. Additionally, a universe of properties can be associated with instances so that the most concrete instances can be directly associated with a collection of defining properties, but more abstract concepts can hold instances with even contradictory properties ("fly"/"not-fly"). Following this idea, traditional cognitive models assume that concepts are in a given state corresponding to an instance. However, such models do not account for the "fallacious" ways people reason with concepts. Hence, the quantum cognitive modeling of concepts extends the notion of state by allowing "instance-state superposition," meaning that a concept can be in a state which does not correspond to any of the instances, but to a superposition of them (i.e., quantum systems can be in multiple states until measured or observed). The latter has been shown to be compatible with how people process meaning in seemingly irrational ways (Aerts et al., 2012).

2.3.2. Context dependence. Context is roughly understood as "the circumstances in which something occurs." In our case, "something occurs" refers to a concept that is being elicited by a human mind. Paradoxically, the notion of context is possibly more vague than the notion of concept itself. Namely, a total of more than 150 definitions have been proposed in different areas such as linguistics, cognitive science, psychology, and philosophy (Stalnaker, 2014). Depending on the area of application, different aspects of what constitutes a context become the focus of the definition. In quantum theory, contextuality is an important feature that distinguishes classical from quantum entities. Technically, it refers to the dependence on the properties of a system with the measurement process. The latter means that a quantum system is able to exhibit different properties depending on how these properties are measured. Contextuality is intimately related to superposition, as measurement is interpreted as an action that induces the "collapse" of the state of the system from the pre-measurement to the post-measurement state. In the post-measurement state the system's properties are determined, but in the pre-measurement state such properties are not necessarily determined and it is even possible that the properties could entail contradictions, as cleverly explained in the Schrodinger's cat paradox (Howard et al., 2014).

In cognition, context entails all the priors at the moment of eliciting a concept (Tulving & Schacter, 1990). A traditional understanding of cognition would assume that such priors interact in a deterministic way with the cognitive state of an individual and thus determine how the individual would act. Such approaches are compatible with a rational-inspired view of cognition, where our minds are nothing but computing machines that follow purely deterministic circuits of information processing. The quantum cognition approach instead brings in contextuality to allow cognitive states to be "out of reality," that is, in superposition states, and formally introduces contextuality as the collapse of such superposition states into concrete instances.

2.3.3. Cognitive processing of meaning is non-compositional. We would like to stress here the fact that the seemingly common nature between quantum and cognitive entities is crucially lying in the fact that, in both situations, there is a mysterious potentiality of the form (represented by the superposition). This can be formally represented by the fact that impossible situations can exist prior to interaction with the context (being a lab detector or a cognitive act of elicitation). Therefore, the interaction of these potentialities in non-compositional ways creates new potentialities that belong to the whole of the combination and not to the parts, referred to as entanglement.

One important difference between the quantum and the cognitive, is that the latter has an extended freedom in choosing properties and states. The extent of admission of impossible situations in our minds, being represented by physical processes (e.g., time-travel) or by abstract or emotional entities (infinite, oxymorons, paradoxes, etc.), is larger than the extent of freedom that quantum systems have. Our cognitive activities do not comply necessarily with the laws of physics, but generally tend to fix, believe, and accept as real what is compatible with our cognitive environment (Leslie & Keeble, 1987). Specially, the non-compositional meanings we create are subjected to the features of our environment and the contextual processes occurring in it.

Specifically, the non-compositional meanings we create are subjected to the features of our environment and the contextual processes occurring in it. The latter is what invites us to reflect on the notion of entangled cognition in immersive environments, as a quantum-cognition-informed extension of our cognitive states. We conceptualize how the phenomenon of entangled cognition can be seen to occur in/within immersive learning environments, when learners/users/agents "switch" from one collapsed reality thread into another, through structural re-coupling between the observer and different observed realities. Moreover, we speculate that the phenomenon of entangled cognition does not occur in/within immersive learning environments only, but thus by default, it ought to occur in all types of environments or "realities" regardless of their nature–whether real, artificial, virtual, or other. Yet here, we focus on the phenomenon of entangled cognition in/within immersive learning environments.

3. Entangled cognition in immersive learning experience

3.1. Quantum footprint in immersive learning and mixed reality

Immersive learning in education can be defined from several perspectives and approaches, for example, from pedagogical, psychological, semantical, technological, or human-computer interaction (HCI) perspectives, to mention some. For some insights on how the term immersive learning has been addressed in education, see Dengel (2022). Here, we understand the term immersive learning as the type of learning that occurs when users/learners engage or interact with immersive technologies, settings, environments, or systems, enabled by digital technologies and affordances. Following the Santiago school of cognition, this view of immersive learning is grounded on the notion that learning is a cognitive process naturally occurring within living organisms entailing the constant co-adaptation and coupling of organisms to their ever-changing environments (Aguayo, 2019; 2023; Maturana & Varela, 1980).

In this context, immersion can be understood as the degree of involvement with digital technology and computer-generated spaces (Jennet et al., 2008). Many perspectives build from the notion of presence, in relation to mental involvement and engagement with new technologies, for example, see Slater (2003) and Nilsson et al. (2016) for some accounts. In education, new and emerging immersive learning technologies such as AR, VR, 360 image, sound and video, 3D modeling and data visualization, smart and wearable devices, Internet of Things (IoT) devices, along with the ongoing growth of artificial intelligence (AI), and machine learning systems, provide a plethora of diverse affordances and opportunities for users to engage with learning in immersive ways (Cowling & Birt, 2020). We conceive immersion here as the type of affordances provided by new digital technologies that can provide a sense of "being there", that is, a lived experience whether in real, virtual, or artificial ways. One of the main advantages of immersive environments for learning is that they can provide rich sensory learning experiences, not only providing better simulation and/or real-life authentic contexts for learning, but also possibilities to enhance deep conceptual thinking (De Freitas & Neumann, 2009). Immersive digital tools can be used to create open-ended, exploratory, self-determined, and/or experiential learning experiences. One type of immersive technology in education is what is known as XR.

Mixed reality can be understood as the blending of real to digital immersive affordances and interaction possibilities, along a reality-virtuality continuum. Mixed reality as a concept was originally proposed by Milgram and Kishino (1994) as a "virtuality continuum" including AR, augmented virtuality (AV) and VR. This original view of XR (abbreviated as "MR") was conceived as any interaction with technology existing along this reality-virtuality continuum between the real world and the virtual world. Today, some authors expand this view and refer to XR as "extended reality" or "XR" (instead of MR), to explicitly indicate the inclusion of both ends of the reality-virtuality continuum, that is, the real world end, or "real environment" (RE), where digital immersion is non-existent, and the virtual world end where digital immersion is at its full, see, for example, Jones et al. (2019). Here we prefer the term "XR" to denote the consideration of the full reality-virtuality spectrum, while acknowledging the merging, weaving and coming together of different reality threads between real and virtual worlds. Figure 2 below shows a contemporary example of the types of immersive technologies and affordances that can be included in an XR continuum in education.

Mixed reality conceived as a new pedagogical substrate, offers a collection of learning affordances blending real and virtual worlds along an immersion continuum (Liu et al., 2017; Speicher et al., 2019). Today, the notion of XR continuum in education goes beyond the idea of providing complementary types of affordances from real to digital along a continuum, to creating and delivering rich and multi-layered "learning contexts" that transcend space and time (Aguayo, 2021; Aguayo et al., 2020; Mann et al., 2018). This requires us to consider an epistemological shift

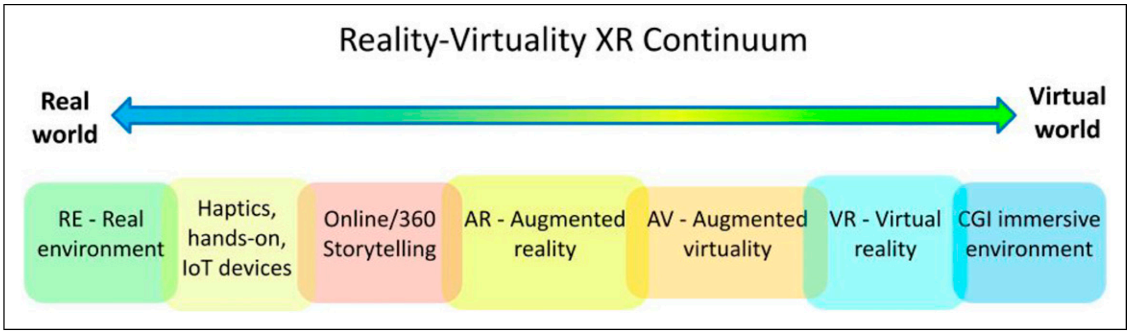

Figure 2. Representation of the reality-virtuality mixed reality (XR) continuum, showing examples of a series of real to digital affordances along the continuum that extends from the real world side (real environment or RE) on the left side, to the fully immersive virtual world side, provided by computer-generated interface (CGI) environments on the right side.

underpinning educational practice, rather than just a shift in practice, where "XR may provide the capacity to move enacted learning from the periphery to the core of learning design" (Leonard, 2020, p. 4), to favor learning instances in which action "is perceptually guided in a world dependent on the perceiver" (Varela et al., 1991, p. 203).

In this view of immersive learning and XR, the 4E cognition framework can help in conceptualizing human experience as a co-created interaction with the lived environment. We also extend our epistemology to incorporate some quantum-rooted aspects to deal with vagueness, contextuality, and non-compositionality (see section 2.3) identifiable in immersive learning environments, indicating a quantum footprint. Therefore, we postulate that immersive learning environments, such as XR learning environments, can present structural, functional, organizational, and meaning-making processes that are quantum-like, and this might be beneficial for the learning experience.

In the same way our reasoning of the meanings that different concepts in our daily life are not sharply defined, neither in their boundaries nor in their implications (Rosch, 1973; Zadeh, 1975), our perceptual and cognitive experiences of unknown real worlds, and of virtual, artificial, and digitally immersive worlds, bring along co-constructed meaning-making processes of the observer with the observed, gradually and subjectively, as we enact the experience. In this scenario, experienced as well as observed concepts bring along with them, in turn, different possible instances of such vague concepts, which from a quantum theory perspective, can be kept in suspension and duality. For example, in different reality settings, where the collapse of states can be enacted by the observer to cohere in a single reality, or maintain isolated unfolding different universes, as in the many-worlds interpretation of quantum theory (DeWitt & Graham, 2015).

Context dependence is also an intrinsic part of human experience within a 4E cognition perspective, as well as from an educational technology perspective in relation to the outcome of the learning process as influenced by the learning context. As understood in quantum theory, contextuality as a feature distinguishes quantum entities from classical entities. In practical terms, this refers to how a quantum system is able to exhibit different properties depending on how it is observed. This in turn brings along the notion of superposition, where the observed is interpreted as an action that induces the collapse of existing possible states of the system. When translating this logic into immersive learning environments, not only do we see how prior the "observation" of the immersive environment all available states to be observed are possible, even contradictory ones. But once the immersive environment is observed, the observer enacts the experience determining the properties of the observed environment. Additionally, the immersive experience allows for unfolding collapses and "replay" reality. This feature can be also extremely important for learning, specially in topics related to causal reasoning.

In the same way research in cognitive psychology has revealed that concept combinations are not compositional in general, similar non-compositionality can be found and seen within immersive and XR environments. Within these environments, different potential "layers of reality" and their set of potential "instances" can be accessed along an experiential continuum. Through a process of structural coupling and interaction between the observer and these superimposed potentialities, a process of entanglement with a collapsed reality is determined, determining in turn the observed immersive "lived experience."

These similarities and commonalities between quantum phenomena and immersive learning not only indicates the presence of a quantum footprint within immersive learning environments, but also offers the possibility to contemplate the presence of an entanglement phenomenon along the different observed reality threads within immersive learning and XR environments. This is what invites us to reflect on the notion of entangled cognition in immersive environments, suggesting that we can conceive novel forms of cognition in/within immersive environments.

3.2. Entangled cognition in immersive learning

Varela (1999) alluding to VR: "what seems most significant to me is the veracity of this world that emerges rapidly, after a few minutes of testing this new situation, we inhabit a body in this new world, and the experience is really that of flying through walls or exploring fractal universes" (p. 58). The immersive experience Varela (1999) describes regarding VR technologies is that the virtuality of an environment is reality for the nervous system. The cognitive agent is the generator of its own worlds, even when it is limited to dynamic loops of structural couplings with immersive technology, or other real physical objects. Following the quote from Maturana and Dávila (2015) stated at the beginning of the article, the cognitive agent sees, lives, experiences, and realizes itself based on what s/he believes is valid, whether fantastic or ordinary, virtual or real.

That "validity of the experience," that of flying through walls or exploring fractal universes, provided by immersive technologies and affordances, becomes our human living-coexistence experience of the world. Our bodily sense-making and sociocultural meaning-making processes embedded in/with the world (Hutchins, 2005); our embodied ecosomaesthetics intertwined with the flesh of the world (Merlau-Ponty, 1964; Thrift, 2008). Our human living-coexistence experience is switched from one reality to another the moment we are structurally coupled and enacted with an extendedly accessed immersive world (Clark & Chalmers, 1998; Varela et al., 1991). At that moment, our cognition becomes behaviorally inseparably coupled to/with a new reality, another reality, an alternative reality, one that can offer several "entry points" to pedagogically concatenated affordances leading to different lively immersive realities and learning experiences along a reality-virtuality XR learning continuum (Aguayo et al., 2018; Aguayo et al., 2020). Here, a meaningful way to describe this new unit is as a global whole encoding the surfacing properties of all entangled entities across time and space, while the XR experience endures.

In such immersive learning environments, human experience is considered embodied, embedded, extended, and enacted to an unveiling set of XR reality threads entailing a co-creation of meaning from the interaction between the learner (the observer) and the set of digital experiences (the observed) (Aguayo, 2020, 2023). Cognition becomes entangled, to a new whole whose properties are only acquired by the learner/observer when that XR immersive reality is observed, lived, engaged with, structurally coupled and enacted, allowing for a whole-like structure to emerge from the interaction of different possible states coming together. Such alternative immersive reality only exists when it is observed, interacted with, entangled with. In this view, the process of entanglement between learners and immersive learning environments can be conceived as a process of correlation or adaptation between the observer and what is observed (Bitbol, 2011). According to QBism, what we understand as "the world" comes from quantum states representing probabilistic expectations of subjective degrees of belief of the agent assigning the state (Barzegar, 2020).

This proposed framework, derived from 4E cognition and quantum theory, permits us to consider cognition and human experience becoming entangled to/with a new global lived alternative reality when immersed in/with immersive learning environments, such as XR environments. We live as valid this emerging alternative reality we can entangle with through the affordances of immersive technologies, where "it does not matter what we believe or do not believe" (Maturana & Dávila, 2015, p. 334), as "the experience is really that of flying through walls or exploring fractal universes" (Varela, 1999, p. 25).

What differentiates the types of cognitive entanglement we see occurring in immersive XR learning environments is that in XR environments these "immersive experience switches" between the real day-to-day natural world and the alternative reality-virtuality worlds, are abrupt and discontinued, many times unfamiliar. Thus, they become noticeable as an "alternative reality." Our view of an immersively entangled learning phenomenon distinguishable in/within immersive XR learning environments is characterized by the presence and permanence of the whole body while transitioning into a new reality substrate. This process occurs by alternating, integrating and anchoring with immersive digital resources, for example, as offered and facilitated by XR learning environments in education (Aguayo, 2019, 2021; Hutto & Myin, 2013).

We go beyond the recognition of the existence of a cognition entanglement-like phenomenon occurring to human cognition and lived experience in XR immersive learning environments. We propose the possibility of at least two entangled levels of a recursive representation of the same phenomenology, in coherence with the incipient quantum cognition literature debates around the relation between quantum structures and consciousness (Atmanspacher, 2020): (1) A "local entanglement" level, or local reality, related to the circular process of self-referenced *perception and action* over a particular situation, substrate, and/or set of learning concepts configuring a given cognitive entanglement during an XR learning experience; and (2) a "global entanglement" level, or global reality, related to the process and phenomena of *human consciousness* within a whole XR learning environment continuum, composed by a collection of all possible local entanglements across a set of existing XR learning affordances within such continuum, accessible and conceived as a whole learning experience on its own.

Here, the local entanglement level distinction is useful to frame human experience and perception as entangled in/

Figure 3. Representation of a "flying through walls" immersive experience situation to denote a "local entanglement" type of entangled cognition in VR (left image copyright: Oculus; right image copyright: Smash It on Google Play Store).

within immersive learning environments at a particular given moment and/or instance of structural coupling between the observer and the observed environment. For example, when a learner/observer is immersed within a virtual/immersive experience narrative of a particular type, such as when *flying through walls*, or when *exploring fractal universes*, as in the quote above from Varela (1999). In those examples, the locality of the entanglement refers to the immersive experience occurring when a learner and/or observer *is* engaged with that particular alternative reality of reality-virtuality origin considering it as valid when living it, while cognitively operating within it, as denoted in Figure 3.

However, the global reality entanglement level distinction, which relates to the notion of the existence of a global state in quantum entanglement, is useful to us in describing the overall learning occurring in/within an immersive XR learning continuum made up of several local realities or experiences, as a whole. From an educational technology and pedagogical digital design perspective, when we consider such global entanglement within an immersive XR learning environment, we can conceive the cognitive process as a global learning process on learners, coming from engaging with different parts of an immersive XR setting. This can be useful to educational technologists and digital designers when conceptualizing what type of learning outcomes can and ought to occur to different and unique learners when designing an immersive learning continuum.

These two entanglement levels are recognizable, for example, in the work reported by Eames and Aguayo (2019; Aguayo & Eames, 2023), in the context of XR immersive learning environments in free-choice marine conservation education. In this project, the immersive XR experience included a real world experiential and hands-on snorkeling experience in a marine reserve, complemented along with haptic, online, digital, AR, 360VR, VR, and XR learning affordances on marine conservation offered as an immersion continuum available inside a marine discovery center for primary students and their parents, as depicted in Figure 4. This XR intervention followed the XR framework presented in Figure 2, in that it provided different interaction options along an immersion continuum, at different times and places. Each entry point along the XR continuum from Figure 2 can be considered as a potential local reality entanglement. The different set of affordances grouped under each entry point can be perceived, entangled with and experienced on its own at a given moment, in unique ways for each observer, producing a particular set of learning outcomes on learners.

Eames and Aguayo (2019) also signal that, to really understand such XR intervention in relation to the learning outcomes (on marine conservation and the promotion of ecological literacy) achieved on learners, the individual aspects of the XR continuum (or set of entry points, as in Figure 2, and as depicted in Figure 4) are insufficient on their own. This led to the "speculation that the continuum might actually exist as a circle rather than a line, in which VR becomes juxtaposed with immersion in the real world" (Aguayo et al., 2020, p. 14). The global learning experience achieved on learners through the XR intervention is better understood "as an inseparable unit of cognitive quantum entanglements," much like the quantum phenomenon of entanglement that occurs within microscopic entities, described in section 2.1. This reference to a circular/global XR continuum, where all possible experiential states reside as depicted in Figure 5, represents what we consider a substrate for a global type of entanglement.

Thus, *learning* viewed as an emergent phenomenon within a blended global XR continuum in/within immersive learning environments, coming from the structural coupling between the observer and a collection of observed XR

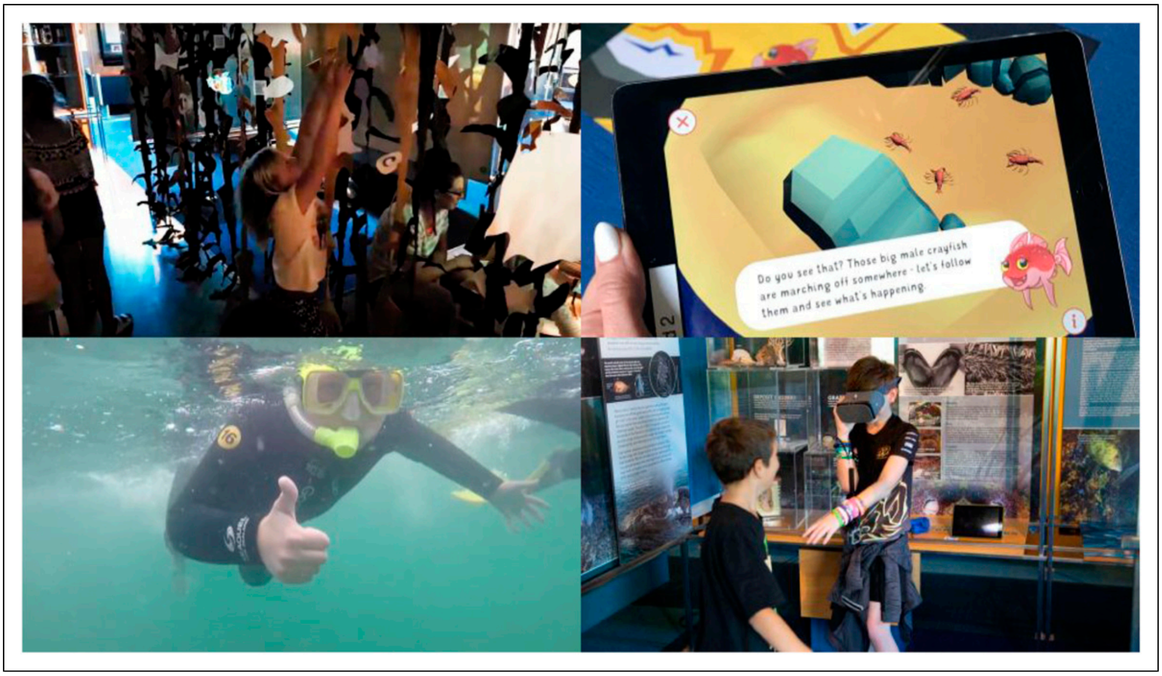

Figure 4. Example of a series of local entanglement instances along an immersive reality-virtuality continuum, constituting a global entanglement whole, from Eames and Aguayo (2019). In clockwise order from the top left image: A haptic instance (on plastic pollution), an AR instance (educating about lobster ecology), a 360 VR instance (presenting different aspects of marine conservation), and a hands-on and bodily immersive experiential instance (snorkeling within a marine reserve) (image copyright: Claudio Aguayo).

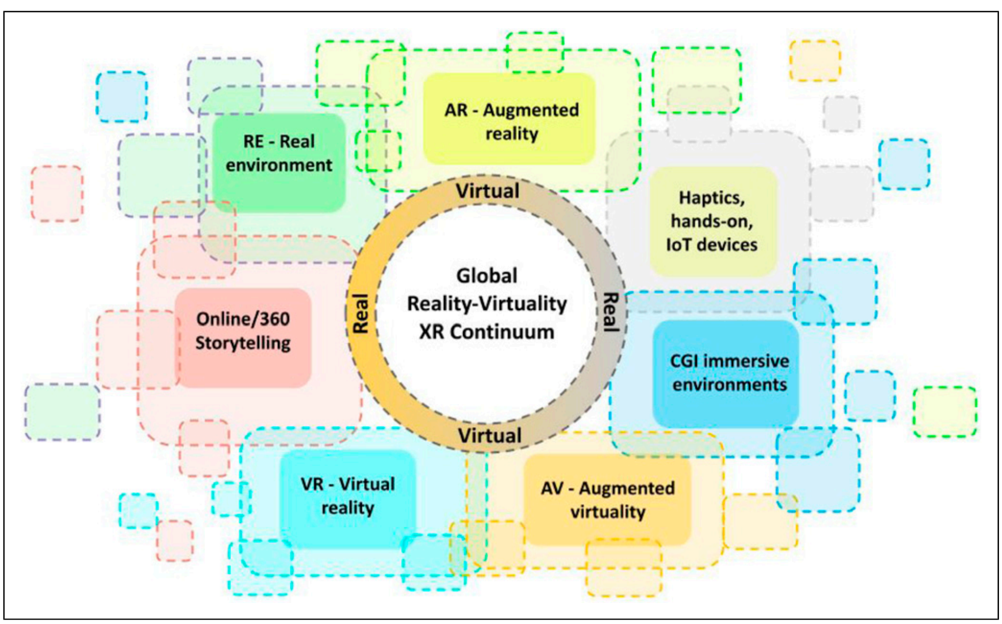

Figure 5. Representation of the linear reality-virtuality immersive XR continuum from Figure 1, considered here as a global reality, that is, a juxtaposed "circular" XR continuum forming a behaviorally inseparable learning substrate entity, entangled to human cognition and consciousness leading to unique learning outcomes for each learner/observer. In this "global reality" level, all available states to be observed are possible, even contradictory ones, but once observed, the observer enacts the experience determining the properties of the observed environment.

substrates (Aguayo, 2019, 2021), offers us as educational researchers and XR designers a different way to conceive the cognitive lived experience of learners within immersive learning experiences. This not only has implications for deeper connections between virtual and real worlds and the possibility to engender learning to socially distributed learning across educational sectors and learning contexts (Eames & Aguayo, 2020), but also to design and develop immersive learning environments accordingly – both requiring a paradigm shift in educational technology research, design, and practice.

Meaningful resonance to such a juxtaposed circular/global XR learning environment can be found in the epistemological departure proposed by quantum theory embracing context dependence and wholeness as fundamental aspects of a reality; as much as it can be found in the fundamental enactivist principle of co-creation of meaning that emerges in the shared interaction between the observer and its environment from the action of perception (Froese & Di Paolo, 2011). This approach is framed from a circular epistemology, in which the observer and the world are entangled in an embodied, embedded, extended, and enacted relational network of action, perception, lived experience, and consciousness.

4. Discussion

Cognitive agents, when coupled with technology, can expand their levels of action, therefore potentially enhancing their learning. New and emerging immersive learning technologies in education provide digital, non-digital, and mixed environments. Here, it is the cognitive agents who experience these environments as digital, non-digital, real or mixed, while living them. There are no objectified environments independently of the cognitive agent. The cognitivist idea of interface, as an independent means that guides the action of agents, does not make sense from an enactive approach. The argument to refute the notion of a cognitivist interface is that physical objects such as technology are not independent of the cognitive agent (Rodriguez, 2021). On the contrary, the notion of immersive enactive learning refers to the entanglement capacity by which cognitive agents enact in a dynamic and relational fashion different ways of perceiving and acting in a digital continuum.

In this article, we outline the idea of entangled cognition to understand the embodied experience of digital imersion in learning environments, when the user/learner switches from the real world reality to an immersive and/or virtual one, and vice versa. We allude to entangled cognition as an underlying process to enaction, by means of structural recoupling between the observer and the newly observed world, the embodiment of perception (embodied-enactive), and the extension of cognition with the material world (embedded-extended). Even though there are tensions in the 4Es of cognition about the representationalist undertones of predictive processing of extended cognition, we argue that quantum theory could fall into this same debate. However, quantum theory and the new advances on the principle of free energy (Friston, 2010), gain more force from the dynamics potential and current states that are not reduced to contentious structures. This is how we encompass from a systemic approach of theoretical integration, which draws on quantum theory, perception phenomenology and cognitive enactivism to highlight entangled cognition in learning environments of immersive digital experiences.

It should be clarified that cognition entangled from the experience of digital immersion, can be metaphorized as the entanglement of strings or threads that are locally invisible in a set of vibrations that connect in advance the agreement of presences between the agent and the digital environment. At a global level, cognitive entanglement can be metaphorized into visible strings that represent a totality of threads that detach, twist, and extend beyond the contingent characteristics of the 4Es. These contingent characteristics that allude to the presenteeism of cognition, usually do not incorporate in their foundations larger time scales such as those proposed by The Material Engagement Theory of Malafouris (2013), quantum entanglement of Qbism (Bitbol, 2021), or at the phenomenological level in the entanglement of Merleau-Ponty (1964). In our proposal for entangled cognition, particularly at the global level, we allude to larger timescales that transcend space and involve stories of connections with things, whether virtual and/or real.

Learning affordances as anchors available in/within an immersive XR learning environment function as perceptible and stable structures for learning abstract concepts in environments with high sensory variability (Hutchins, 2005). "The combination with material anchors can increase the stability of the conceptual structure, allowing more complex reasoning processes" (Hutchins, 2005, p. 1562; Videla et al., 2021), which seems to be a possible mechanism through which learners can switch from one reality to another alternative reality in/within immersive XR learning environments. In this way, the dynamic integration of the perception-action circular epistemology with immersive technologies reconfigures the perception of a given reality by participating in a loop of reciprocal movement restrictions that make it possible for a new alternative reality to happen.

This dynamic process is characterized by the functional reorganization of the agent-technology dynamic structural coupling loop, as a process of immersion-commitment-permanence and subsequent entanglement. Based on the literature and set of premises presented in this manuscript, it is likely that quantum models might better encode features related to the entanglement between the environment and the perception-behavior configuration of users within immersive learning environments. We explore the XR construct in light of enactive cognition and quantum cognition to open new discussions about the potential of 4E cognition. Likewise, when exploring technologies in which digital content is superimposed in REs such as XR, it is interesting to explore whether 4E cognition can support additional explanatory pathways in enactivism such as entangled cognition to understand immersive learning. Following Ingold (2008), life is intertwined at different levels that allude to the paradox of living outside and inside as real; see the argument of our paper, in which we propose that wearing XR glasses to explore the real world, it allows us to live both worlds from the possibilities of our perception. This leads to the dissolution of independent reality to admit the paradox of two levels that overlap from the agency of the perceiver, bringing as many realities as ways of perceiving

We postulate here that cognition is enacted as much as is entangled. Entanglement resides in the enactment of cognition with the perceived reality available as a substrate for cognition, observable when learners engage with immersive XR learning environments offering alternative sets of reality. We recognize at least two entanglement levels of a recursive representation in nature occurring in XR immersive learning environments, that is, a local reality entanglement and a global reality entanglement. Ultimately, these two recognizable levels of cognitive entanglement occurring in XR are particularly useful when designing, and understanding, educational XR learning environments, as during design decision-making processes educational technologists and XR designers can better target their meaning-making design to both designing for a local reality correlated with a global reality, and vice versa. We see the exploration of entangled cognition in XR learning environments as an intriguing and fruitful study direction.

The framework proposed here ought to be explored beyond the realm of immersive learning technologies. The implications of considering entangled cognition as a constitutive quantum-like mechanism underlying our day-to-day enactment with the world invites intellectual exploration across different fields. In education, such a framework provides ground for us to reconsider how we conceive the dynamics occurring around the learner, the learning process and the learning context. In turn, such an understanding of the learner, the learning and the context can guide the creation and design of educational interventions where harnessing the entanglement of cognition, with or without immersive technologies, can potentially enhance and even transform the learning process within educational institutions as conceived today. In particular, exploring different ways to "activate" such entangled cognition switch between different realities following different pedagogical principles (e.g., gradually, lineal/non-lineal scaffolding, discipline/topic-integrated, or in culturally responsive ways) provides promising prospects when it comes to designing targeted learning experiences.

Yet much more is still to be inquired and discovered, in a time of increasingly sophisticated new technologies, affordances and AI systems periodically becoming available to educational practitioners, technologists, designers, and developers for the design of novel learning experiences in education. We see the proposed framework on entangled cognition in immersive learning as a useful approach to guide and encourage design principles accounting for a quantum-like phenomenon in human experience in digital contexts and spaces. We do this grounded on systemic principles from the Santiago school of cognition, the 4E cognition framework, and quantum theory.

It is important to clarify that this theoretical proposal is an exploration of theoretical models that exhibit analytical convergences, and that it can even be considered in a complementary way. Therefore, the theoretical research objective is not based on revealing a different and refuting proposal of the auxiliary hypotheses of the 4E research program. Rather, we seek to open a new hypothesis in light of approaches such as quantum cognition that can additionally contribute to understanding the phenomenon. In the same way, we consider it relevant to incorporate in the future microethnographic descriptions that contribute to the historical-cultural understanding of global changes in perception and action with immersive technologies.

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ORCID iDs

Claudio Aguayo https://orcid.org/0000-0003-1805-7737
Ronnie Videla-Reyes https://orcid.org/0000-0002-1038-2968

Notes

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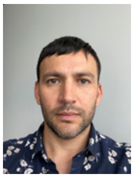
About the Authors



Claudio Aguayo is a Senior Digital Innovation Advisor in Te Ara Poutama, the Faculty of Māori and Indigenous Development at Auckland University of Technology (AUT), Auckland, Aotearoa New Zealand. As a biologist trained in the Santiago school of cognition with a PhD in Education, Claudio draws on distinct interdisciplinary areas to explore how digital tools can be best designed to enhance human experience in digital learning environments. Claudio is the Director of Research and Development for AUT's AppLab, where he leads the exploration and growing understanding of the design and application of new digital technologies for learning in a range of educational settings. His work engages in practice-based research and applied critical making in diverse areas, including: mixed and extended reality in education, socio-ecological sustainability, art+science, culturally responsive design practice, indigenous worldviews, and enactive and embodied cognition in digital spaces, among others.

Ronnie Videla-Reyes has a PhD in Education from the Autonomous University of Madrid, Spain. He is a researcher at the Faculty of Education of the Santo Tomas University, Chile, and Faculty Member at Buckminster College in Brussels. His research interests are the 4E approach applied to STEAM Education and the Pedagogy of Uncertainty. He has been trained in the fundamentals of cultural biology with Humberto Maturana and Ximena Dávila at the Escuela Matríztica. Additionally, Ronnie Videla is the founder of InnovaSteam Lab for the design of interdisciplinary and embodied educational environments with emergent technologies.

Tomas Veloz is the director of Mathematical Modeling of the Centre Leo Apostel, Vrije Universiteit Brussel, Belgium, assistant professor of the Mathematics Department at the Metropolitan Technical University, Santiago, Chile, and lecturer at the Biology Department of the Andres Bello University, Santiago, Chile. He has a PhD in Interdisciplinary Studies and an MSc in computer sciences, with majors in mathematics and physics. His research focuses on interdisciplinary mathematical modeling. His main research areas are Chemical Organization Theory, where he has proven mathematical results such as the decomposition theorem and the existence of quantum-like organizational structures; and quantum cognition, where he has developed methods to represent collections of concepts in a Hilbert Space, and has shown that various cognitive and language phenomena exhibit quantum structures. Additionally, Tomas Veloz is the founder and director of the Foundation for Interdisciplinary Development of Science, Technology and Arts (www.dicta.cl), a Chilean foundation which collaborates with CLEA and several other institutions worldwide to generate and disseminate integrated knowledge, and to develop projects with social impact.