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Three Perspectives on Embodied Learning in Virtual Reality: Opportunities for Interaction Design

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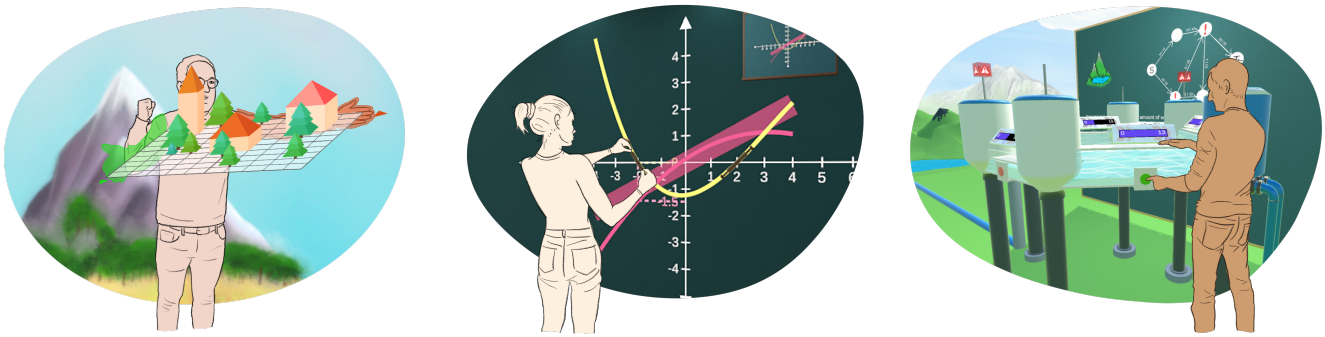

Figure 1: Our paper presents an interdisciplinary framework for embodiment and discusses design opportunities for Virtual Reality (VR) embodied learning interactions through use cases such as: (a) the digital avatar is used to embody mathematical concepts, (b) the learner interacts with mathematical objects [8], (c) the virtual world grounds abstract mathematics in embodied concreteness, that is a highly embodied, situated and relatable context [10]. Images adapted and used with authorization.

ABSTRACT

With the fast evolution of Virtual Reality (VR) technology, new prospects opened for embodied learning. Learners can now manipulate digital representations of abstract concepts and make sense of them through sensorimotor stimulation. However, in research, embodiment is explored from several perspectives, which, we argue, should be considered within a same framework. In this paper, we describe three major perspectives relevant for embodied learning in VR: embodied cognition, embodied interaction, and avatar embodiment. We organize these perspectives within one common interdisciplinary framework, and discuss resulting design opportunities for VR embodied learning interactions. Specifically, we show that embodied interaction does not necessarily support embodied cognition, and that breaking recommendations of avatar embodiment can actually support meaning-making. We believe our work offers novel avenues for future research and will foster interesting conversations in the HCI community.

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CCS CONCEPTS

• **Human-centered computing → Human computer interaction (HCI)**; *Virtual reality*; HCI theory, concepts and models; *Gestural input*.

KEYWORDS

embodied cognition, embodied interaction, avatar embodiment, virtual reality, learning sciences

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1 INTRODUCTION

Embodiment is a growing area of research in several fields such as learning sciences [44], interaction design [13], Virtual Reality (VR) [27], linguistics [22], robotics [12], and more. Each of these fields offers a unique perspective on embodiment, and, although there are some commonalities, these approaches to embodiment should not be used interchangeably.

In our work, we are interested in embodied learning in VR, and we argue that within this area already, several perspectives on "embodiment" are of crucial importance, and that acknowledging the differences between these perspectives can improve interaction design, but also open novel avenues for research.

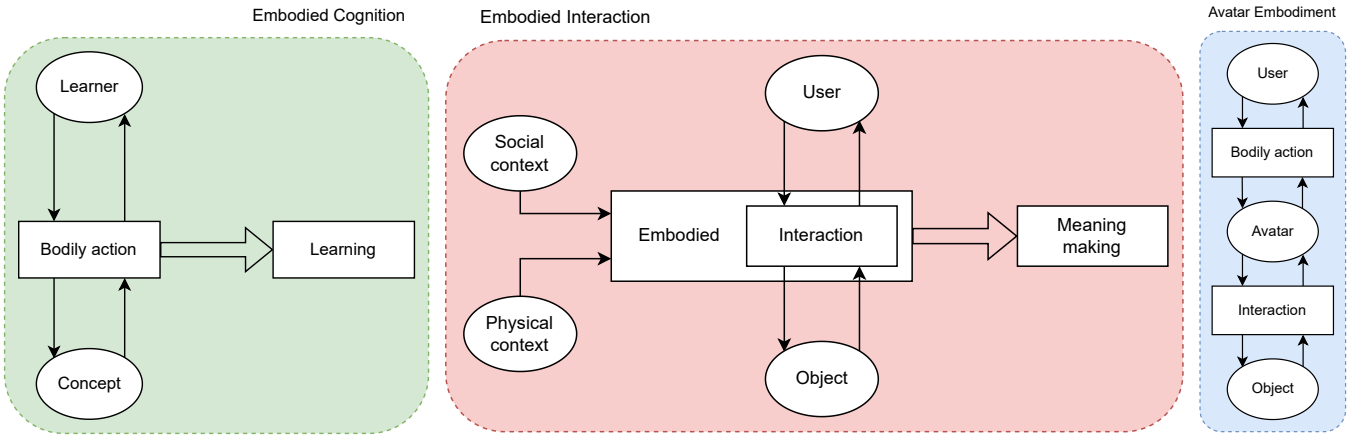

Figure 2: Representation of (a) embodied cognition, (b) embodied interaction, and (c) avatar embodiment. Ellipses represent actors, rectangles represent processes. The relation $A \rightarrow B$ means that A informs B, while $A \Rightarrow B$ means that A induces B. All arrows are conditional, e.g. a certain process may happen but does not necessarily.

To organize our work, we adopt an interdisciplinary approach informed by Learning Sciences, Human-Computer Interaction (HCI) and VR literature, and we focus on three lenses respectively: "embodied cognition", the role of one's body in their learning, "embodied interaction", the role of one's body in making sense of interaction, and "avatar embodiment", the connection between one's body and their digital counterpart.

Although these three approaches to embodiment play a major role in VR embodied learning, they are rarely acknowledged together or put in contrast with one another. For example, recent reviews of embodiment in digital solutions consider either one or two of these perspectives, but never all three aspects [3, 14, 35]. Moreover, to our knowledge, no research explicitly discusses the gap between these perspectives nor the implications of such interdisciplinary approach on interaction design.

In the following, we argue that these three perspectives to embodiment should be considered when designing embodied learning activities in VR. Specifically, we ask: How can interaction research benefit from an interdisciplinary approach to embodiment? The goal of this work is to (1) clarify and organize the terms "embodied cognition", "embodied interaction", and "avatar embodiment" within one framework, (2) illustrate the importance of these three perspectives in the design of embodied learning activities in VR, and (3) foster future conversations at the interplay between these approaches.

2 THEORETICAL FRAMEWORK

With this work, we focus on three meanings of the term "embodiment": embodied cognition, embodied interaction, and avatar embodiment. In this section, we clarify these terms and anchor our work in the embodiment landscape.

2.1 Embodied Cognition

Although experts do not always align on embodied cognition theory and its implications [17], there is evidence that learners' bodies play a role in learning [16, 20, 28, 45]. Specifically, the embodied account of cognition rejects the separation between mind and body, and claims that ignoring learners' bodies is detrimental to learning [38]. While embodied cognition theory has applications beyond our current context, we focus on its role in embodied learning.

The process of embodied cognition then goes as follows (Figure 2.a): When learning about a concept, learners spontaneously perform bodily actions, and in turn, learn through their bodily actions [61]. Let us consider the following example: a learner is counting the number of apples in her basket. To do so, she extends 3 fingers, 1 per apple. Her hand now represents the content of the basket and the quantity 3. In turn, her parent drops another apple in the basket. Our learner then extends a new finger, observes that she now has 4 fingers extended, and may learn that $3 + 1 = 4$.

In addition, research on gestures shows that, when learning a new concept, learners are first able to convey their understanding in gesture, before they can express it in speech and writing [51]. From this perspective, thinking is a form of "truncated action": thinking is an internal expression of a physical action truncated before the physical engagement of the body [2]. Concretely, next time our learner will count apples, she will plan the execution of the finger counting bodily actions, but not actually externally execute it.

Embodied activities support learning in various ways [48, 58]. Embodying concepts supports learners by providing a language to reason about these concepts, before introducing symbols and formalisms [43]. Similarly, embodied learning makes abstract concepts more tangible, more relatable, and therefore more concrete [10, 44]. Finally, embodied learning alleviates cognitive load by enabling storage of information in bodies and objects. For example, our learner embodies basic arithmetic using her fingers, and uses this representation to express her preliminary understanding of quantities, simulate basic operations, and store units for further computations.

Conceptually, embodied learning relies on three main mechanisms [29]: "direct state induction", the induction of certain feelings through bodily states independently of higher cognitive processes;

"modal priming", the activation of abstract concepts through sensorimotor states, often via embodied metaphors which relate concepts to patterns of bodily experience [30]; and "sensorimotor simulation", the simulation of previous bodily actions resulting from a same stimulus, aligned with the truncated action perspective.

When it comes to designing learning activities, the process of embodied learning can be considered from two main perspectives: spontaneous bodily actions and directed bodily actions.

First, learners spontaneously perform gestures and body movements while reasoning about concepts. Therefore learning activities and their context should facilitate gesture production. For example, Tancredi et al. designed a balance board input device utilizing learners' need for sensorimotor regulation as part of the learning process itself [57].

Second, learners make sense of concepts by observing bodily actions. Such actions can be produced as directed per an interactive learning activity. For example, in *The Hidden Village*, learners are explicitly taught gestures to represent geometrical concepts and, in turn, perform better proofs [45, 55]. In contrast, the *Mathematical Imagery Trainer* directs learners to move their hands in front of a screen so that it remains green [20]. By observing the consequence of their physical movements, students make sense of the concept of proportions. Although none of these bodily actions are spontaneously produced, they serve as anchors for future reasoning.

2.2 Embodied Interaction

Interaction is informed by and grounded in its physical and social context [13]. Let us consider the pinching gesture, performed by varying the distance between thumb and index finger. This gesture is often used on mobile devices to zoom in and out. While this gesture is not natural, as it is not used for this purpose in the non-digital world, it gains meaning through its physical context. As the gesture is performed on a flat and smooth surface, the fingers metaphorically stretch and compress the underlying digital space.

Dourish claims that "embodied interaction is the creation, manipulation, and sharing of meaning through engaged interaction with artifacts" [13]. Here, Dourish emphasizes engaged practice, as opposed to "disembodied rationality", and insists on meaning creation [13]. In our representation (Figure 2.b), the user interacts with an object. This interaction is embodied: it is informed by a social and a physical context. Through this process, meaning-making may occur: that is, the user may make sense of the interaction.

Dourish lists several design principles [13]: the meaning of the interaction should arise on multiple levels; users, rather than designers, should create and communicate the meaning; and the interaction should turn the action into meaning. Therefore, interaction design serves as a scaffold, rather than a guide, to the meaning-making process. Moreover, it is important to note that the meaning highlighted here is the meaning of the interaction, the experience, not necessarily the meaning tied to the concept being learned.

Embodied interaction also means that interaction design should be informed by considerations related to users' bodies. For example, Höök describes somaesthetic appreciative design, an approach including the users' bodies, and their bodily experiences, from the beginning of the design process [19].

Similarly, Mueller et al. present the distinction between the physical body, the *Körper*, and the feeling body, the *Leib*, and argue that embodied interaction design should focus on the *Leib* perspective [41]. Let us consider the design of a "next level" button in a learning game. Considering the *Körper* perspective, one might place the button close to the resting position of the hand to avoid tiring the learner. However, considering the *Leib* perspective requires us to empathize with the learner. At this stage, the learner solved a complex problem, possibly after several attempts, learned something new and accomplished something difficult: They feel proud. As a result, the button should be placed up high, inviting the learner to adopt a "winning pose". Considering the *Leib* perspective is also relevant as it can activate the direct state induction mechanism of embodied learning [29].

Generally, HCI researchers have been insisting upon the importance of involving users' bodies in the interaction with digital content, although this aspect is still under-theorized [53].

2.3 Avatar Embodiment

The definition of avatar embodiment depends on digital avatars, and thus on digital interactive solutions. In this section, we start by briefly defining VR, then, we define avatar embodiment and discuss the relevant design considerations.

Fundamentally, VR separates the user from the real world and immerses several of their sensory channels, e.g. visual and auditory, into the virtual environment [40]. VR has been implemented in various ways [42], and Head-Mounted Displays (HMDs) are one of the main tools to access VR [39]. VR can integrate a wide variety of input signals: hand-tracking [59], eye-tracking [11], physiological sensors [49], or haptic feedback [54]. Finally, VR can support embodied interaction by integrating the physical context of the interaction [49], as well as its social context [33, 62].

Regarding embodied learning, VR is particularly interesting as it involves high immersion and high sensorimotor stimulation [24], supports both spontaneous and directed bodily actions thanks to hand-tracking and natural interaction [15, 59], gives access to experiences that would be dangerous or impossible in the real world [7], offers concrete and embodied representations of abstract concepts [10], and provides a safe space for exploration without fear of harm, failure, or judgment [60].

While considering these benefits, it is important to remember that users cannot see their own bodies. Instead, they see a virtual avatar instead, through which they manipulate the virtual environment: A user performs bodily actions, as a puppeteer, these actions inform a digital avatar, which, in turn, interacts with the digital object (Figure 2.c). This impacts user experience as it influences their proprioception, especially for users with high body awareness [8, 52].

In this context, the sense of avatar embodiment describes the connection between user and avatar, and is defined as [27]: "The Sense of Embodiment towards a body B is the sense that emerges when B's properties are processed as if they were the properties of one's own biological body."

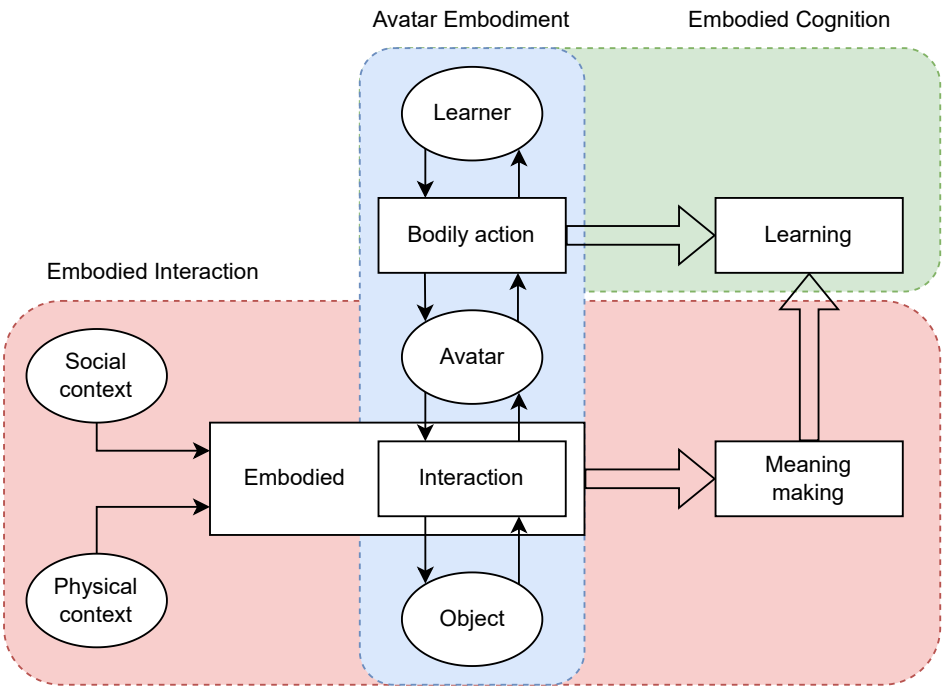

Figure 3: Representation of our framework for embodied learning activities in VR. Ellipses represent actors, rectangles represent processes. The relation $A \rightarrow B$ means that A informs B, while $A \Rightarrow B$ means that A induces B. All arrows are conditional, e.g. a certain process may happen but does not necessarily.

The sense of embodiment is based on three components [27]. The sense of self-location relates to how the digital personal, peripersonal and extrapersonal spaces are perceived in relation to their non-digital counterparts. The sense of agency relates to the sense of being in control of the digital avatar, at a motor level. Finally, the sense of body ownership relates to whether or not users attribute the digital avatars as part of their own bodies. Recent work defined standardized instruments to measure the sense of avatar embodiment, and focuses on constructs such as the sense of body ownership, the sense of body agency, and the sense of body change [18, 46, 50].

To achieve a high sense of avatar embodiment, it is recommended to consider the user's perspective in the activity, the sensory consequences of their actions, as well as the morphological similarity between the digital avatar and the user's body [27]. In particular, there is an important issue in the field as the diversity of bodies is not sufficiently accounted for [25, 53].

2.4 Landscape of embodied learning in VR

These three lenses can be combined within one framework where embodied cognition focuses on the role of bodily actions in learning, embodied interaction addresses to the role of physical and social context in giving meaning to interaction, while the embodied avatar connects bodily actions and interaction (Figure 3). However, the distinction between them is important as, for example, designing for embodied interaction does not necessarily support embodied cognition [8], and designing for avatar embodiment does not necessarily support embodied interaction [9].

To acknowledge this distinction, we built our framework representation (Figure 3) through several iterations informed by the presented literature as well as two constraints: the representation should be (1) specific enough to include the core elements of each perspective on embodiment, and (2) general enough to cover various scenarios of embodied learning in VR.

3 OPPORTUNITIES FOR INTERACTION DESIGN

In the following, we discuss several use cases, tied to different paths within our framework. Many more examples could be discussed. Our goal here is not to provide an exhaustive overview of embodied learning in VR, but to highlight the relevance of such an interdisciplinary approach and generate fruitful conversations within our community.

Therefore, we selected paths covering several approaches to embodiment and emphasizing their commonalities and differences.

3.1 From bodily actions to learning: Two pathways to learning

In our framework, we distinguish bodily actions and interaction. This distinction is important and can be used to explain previous empirical results. A recent study explored the difference between position-focused embodiment and movement-focused embodiment in an intuition building activity about derivatives, in VR [8, 37]. In this work, students manipulate the derivative at certain points

of a curve to solve puzzles (Figure 1.b). In the position-focused approach, the learner rotates a handle to adjust the derivative, and the position of the learner's hand is congruent with the derivative, which, the authors argue, highlights derivatives as slopes. In the movement-focused approach, learners drag a point to draw the derivative, and the movement of the learner's hand is congruent with the derivative, thus highlighting derivatives as variation rates.

An empirical study revealed that the movement-focused approach resulted in poorer learning outcomes [8]. These results can be explained with our model. As described by the authors, at the bodily actions level, position-focused embodiment emphasizes slopes, while movement-based embodiment emphasizes variation rates. However, at the interaction level, the meaning of the interaction is gained in a digital context highlighting derivatives as slopes. Indeed, the interaction happens at specific positions on the curve, with no notion of spatial or temporal progression.

In conclusion, in the position-focused case, the meaning highlighted by the interaction is congruent to the one highlighted by the bodily actions, and therefore supports two pathways to learning, represented in our model by `Bodily action` ⇒ `Learning` and `Interaction` ⇒ `Meaning making` ⇒ `Learning` (Figure 3). In contrast, in the movement-focused approach, the two paths are not congruent and result in poorer learning outcomes. In conclusion, when designing embodied interaction, one ought to consider how the meaning of the interaction relates to the meaning of the concept being learned.

3.2 From context to learning: Embodied concreteness

Moving in a learning activity is not enough, social and physical context of learning matters as well: "much of what is learned is specific to the situation in which it is learned" [4, 23]. In this regard, the context of the interaction is both important from an interaction perspective and a cognition perspective. This connection has been highlighted before. Chatain et al. described how the context of embodied interaction can be designed to support grounding of abstract topics in embodied concreteness, "a form of concreteness that involves a high degree of embodiment, in a situated and relatable context" [10].

In their work, the authors designed an embodied activity to learn about the max flow problem in graph theory and compared two conditions involving bodily actions: In the first condition, learners manipulate a geometrical representation of a graph. In the second condition, the graph representation follows an embodied "water flow" metaphor to activate the modal priming mechanism. In this condition, learners manipulate a pipe system to transport the maximum amount of water from a lake to a city, in a highly embodied setting (Figure 1.c).

The results of this study show that when the context of the interaction was designed according to embodied concreteness, students found the activity more relevant, felt more prepared for the subsequent lecture, and had significantly higher learning outcomes.

If we consider these results within our framework, both forms of embodied interaction are meaningful, in the sense that the movement of the body is congruent with its effect on the virtual world. This supports the following path in our framework: `Context` → `Interaction` ⇒ `Meaning making` ⇒ `Learning`. However, in the embodied concreteness condition, the context also gives meaning to the bodily action through modal priming, and activates the following path: `Context` → `Interaction` → `Bodily action` ⇒ `Learning`. Therefore, when designing the context of the interaction, mechanisms of embodied cognition should be considered.

3.3 From bodily actions to object: Desirable difficulties

Generally, embodied interaction does not necessarily support embodied cognition, and desirable difficulties should be considered. Desirable difficulties are difficulties that "trigger encoding and retrieval processes that support learning, comprehension, and remembering" [6]. We argue that short-comings in usability can actually benefit embodied cognition.

As an example, Abrahamson et al. underline the importance of the distinction between proximal movement and distal movement [1]. When interacting with an instrument, proximal movement is performed by the learners to interact with said instrument, while distal movement is the actual effect on the world. In our framework, proximal movement can be described as `Bodily action`, while distal movement can be described as `Interaction` → `Object`. The gap between proximal and distal movement, they argue, is where sense-making happens. Considering a circle drawing activity: In one condition, learners use one finger to draw a circle, while in a second condition, learners draw a circle using two fingers moving along the x and y axes. In the first condition, there is virtually no gap between proximal and distal movement. However, in the second condition, there is space for sense-making as learners make sense of circles within a Cartesian coordinate system.

Exploiting this same gap, another way to introduce desirable difficulties is through temporal distance. As discussed before, embodied learning happens via two kinds of bodily actions: spontaneous and directed. In an embodied interaction context, bodily actions are often directed by the interaction. While this approach is useful for intuition building, adding a delay between bodily action and subsequent interaction feedback can give space to reason about the bodily actions and their effect at a deeper level, and, therefore, result in learning [8].

3.4 From avatar to meaning making: Meaning in morphological divergence

Research in avatar embodiment highlights the importance of morphological similarities between bodies and their avatars [27]. Differences have been explored, but previous research mostly focused on embodying other bodies [5, 26]. However, altering avatar appearance can actually give meaning to embodied interaction, through `Avatar` → `Interaction` ⇒ `Meaning making`. For example, Pei et al. explored hand interfaces for expressive interaction [47]. In their work, embodied metaphors transform users' hands into 3D tools and animate these tools, for example mimicking scissors to cut through digital content. This approach is particularly interesting as it is grounded in common and relatable embodied metaphors, but also because it can be used to provide haptic feedback without supplementary equipment. For example, users can feel that the scissors are closed as their fingers end up touching each other.

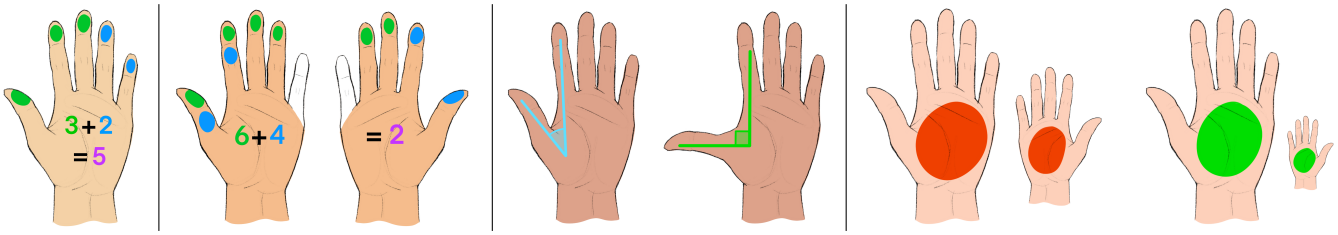

Figure 4: Examples of hand-based semantic avatars: finger counting in $\mathbb{N}$, in $\mathbb{Z}/8\mathbb{Z}$, embodied protractor, and first person *Mathematical Imagery Trainer* [20].

Alteration of avatar appearance for embodied interaction has also been explored in 2D. With Digital Gloves (***DigiGlo***), input and display are co-located on the hands of the user [9]. As an example, the authors describe *Space Traveller*, an on-hand pinball game where players navigate a spaceship across their hands by activating bumpers on their wrist, and capture items on their palm and fingers. In this game, gestures gain new meanings: for example, connecting the index finger to the thumb in a loop creates a passage between two areas of the play-field.

In conclusion, breaking morphological similarities between avatars and bodies can be an interesting way to support novel and meaningful embodied interaction.

3.5 From avatar to learning: Semantic avatars

Although previous research has explored the role of avatar embodiment on presence and cognitive load [36], we did not find work focusing on conveying meaning through digital avatars in a learning context. In this section, we explore the path `Avatar` $\rightarrow$ `Bodily action` $\Rightarrow$ `Learning` and offer a novel avenue of research to address this gap: "semantic avatars", digital avatars designed to highlight a specific meaning, explored through bodily actions (Figure 4).

In VR, most avatars at least have hands. In this context, ***DigiGlo*** can support sense-making of arithmetic through object collection [31], in a finger counting task (Figure 4.a). Moreover, previous research showed that VR can increase body ownership towards a hand with six fingers [21]. Therefore, one could design a semantic avatar with four fingers per hand to support embodied meaning-making of base-8 counting (Figure 4.b). With semantic avatars, learners could spontaneously generate meaningful gestures that would be meaningless with their physical bodies only.

Hand-based semantic avatars can also be used to revisit previous embodied learning activities. For example, in *The Hidden Village* [45], the hand of the learner could become a tool to highlight angular behavior by displaying the nature of the angle between two fingers (Figure 4.c). This approach could also offer a first-person perspective and reduce split attention effect [56] in the *Mathematical Imagery Trainer* [20] as the reference point would be embodied by the learner directly, and the feedback would be displayed on the hands, rather than on an external screen (Figure 4.d).

In addition, full-body semantic avatars can be explored. For example, using an avatar with stretchable arms learners could embody a space's referential and learn about 2D linear algebra (Figure 1.a). Such an avatar could activate the direct state induction mechanism of embodied learning: as learners move their arms to transform the space, they perform flexor and extensor movements and activate approach and avoidance processes [34].

Generally, we believe that embodiment research would benefit from considering digital avatars designed specifically to convey meaning, rather than only realistic avatars used as a manifestation of users in the virtual world.

4 DISCUSSION AND CONCLUSION

In this work, we described three approaches to embodiment: embodied cognition, embodied interaction, and avatar embodiment. We showed that, although only a subset of these are discussed in VR embodied learning research, the gap between them has implications for interaction design and offers novel research areas. To address this we offered an interdisciplinary framework for embodied learning and described its relevance through several use cases.

From this we draw specific design considerations for VR embodied learning interactions: (1) consider the meaning highlighted by the interaction and its context and how it relates to the meaning being learned, (2) consider desirable difficulties in interaction to support deeper sense-making of bodily actions, and (3) consider breaking avatar-body morphological similarity to design semantic avatars, i.e. avatars designed to apprehend a specific concept and highlight a specific meaning.

More generally, users' bodies are heavily involved in embodied learning activities in VR and should be acknowledged throughout the design process. Considering our three lenses, several questions can be asked. First, we suggest questions focused on embodied cognition: Are spontaneous bodily actions considered and supported in the activity? Are specific bodily actions elicited by the activity and if yes, do they support learning? Second, we suggest questions related to embodied interaction: Are the physical and social contexts, both in the real and the virtual worlds, considered in the activity? How do bodily actions support meaningful interaction in said context? Does the meaning of the interaction support learning? Third, we focus on avatar embodiment: Does the avatar support learners at they make sense of bodily actions as well as interaction?

We should also stress that learners bring individual differences that must be considered when designing VR embodied learning activities [25, 53]. Learners may differ in age, gender, ethnicity, background, but also in cognitive and physical characteristics. From a representation standpoint, these differences already impact avatar design [32]. From an embodiment standpoint, further considerations should be acknowledged. Specifically, physical differences

may result in different bodily actions, both spontaneous and directed. Moreover, as meaning-making in embodied activities is tied to bodily actions, physical differences may impact meaning. We believe future work would benefit from these considerations, for example, semantic avatars could be designed to accommodate for learners' unique sensorimotor perspectives. Similarly, the role of the social context in our framework should be investigated in more depth, specifically as some learning activities are designed for classroom settings.

However, we believe our work can already foster interesting discussions in the HCI community, support novel avenues of research, and strengthen future work. Moreover, although we focused on embodied learning in VR, we believe that our approach can be further generalized. First, subsets of the framework can be used in more general settings. For example, leaving a VR context, other embodied learning activities can be considered by omitting the avatar component and focusing on interaction realized through bodily actions in context. Second, other fields may benefit from a clarification of the different meanings of embodiment and the influence of an interdisciplinary approach on design considerations. For example, this has been explored in robotics, where embodiment may be considered from a purely functional and mechanical perspective, focusing on sensing, manipulation, locomotion, and haptics, but also from an Human-Robot Interaction (HRI) perspective, focusing on robots as a manifestation of an interactive agent in a physical and social context [12].

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