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Learning of Abstract Concepts through Full-Body Interaction: A Systematic Review

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ABSTRACT

Over the past ten years several learning environments based on novel interaction modalities have been developed. Within this field, Full-body Interaction Learning Environments open promising possibilities given their capacity to involve the users at different levels, such as sensorimotor experience, cognitive aspects and affective factors. However, Full-body Interaction is still a young field and research on design and assessment methods offers a fragmented panorama from which it is not possible to derive clear research solutions. Starting from this necessity, we present a systematic review of educational applications developed as Full-body Interaction and the results of their empirical evaluation. Our analysis offers instruments to systematize the multiple aspects involved in the design and assessment of Full-body Interaction Learning Environments and provides guidelines for novel research paths.

Keywords

Full-body interaction, Whole-body interaction, Embodied interaction, Technology-enhanced learning

Introduction

For several years technology-enhanced learning has mainly focused on the content of the interaction, relegating the physical interface and the interaction modality to a pure instrumental role. However, over the past years, under the term of “Embodied Interaction” - defined as “*the use of the physical world to interact with digital technologies*” (Dourish, 2004) - several Learning Environments based on novel interaction modalities have been developed. Promising possibilities can be found in Full-body Interaction, understood as *using the movements and the actions performed in the physical space by the body of the user, as mediators of the interactive experience*. From a theoretical perspective Full-body Interaction has the potential to support learning (Revelle, 2013) by involving users at different levels such as sensorimotor experience, cognitive aspects and affective factors.

In this context an increasing number of Full-body Interaction Learning Environments (FUBILEs) have been designed to support learning. However, due to its novelty, findings related to its evaluation do not allow identifying effective and generalizable design strategies. This situation offers a fragmented panorama from which meaningful conclusions about design choices may not be deduced.

Starting from this necessity, we present a systematic review of educational applications developed as Full-body Interaction Learning Environments and aimed at fostering the learning of abstract concepts. A total of thirty selected papers, published during the last ten years, have been reviewed. The purpose of the review is to provide a clear systematization of theoretical approaches, design strategies and evaluation methods for FUBILEs. The analysis shows the effectiveness of FUBILEs in engaging learners and in grounding abstract concepts. Furthermore, it allows us to formalize guidelines for designers and paths for future research especially in the fields of design, evaluation methods and comparative studies.

Method of analysis

This article reviews studies published in the last ten years (2003-2013) related to the use of Full-body Interaction for learning of abstract concepts. The literature reviewed proceeds from peer-reviewed studies published in English in scientific journals, proceedings of international conferences, symposia and book chapters. The search was carried out through the consultation of the following online databases of academic resources: ERIC, JSTOR, PapersFirst, ACM, IEEE, WilsonWeb, Elsevier, InformaWorld, Mary Ann Liebert, SpringerLink, Wiley Interscience, MIT Press and SAGE.

The initial research was based on searching the terms "*learning*" and "*education*" combined with the keywords: *embodied interaction, full-body interaction, whole-body interaction, motion-based interaction, gesture-based interaction, bodily interaction, and kinesthetic interaction*. We then searched for articles cited in the initially found papers.

The selection was based on the inclusion criteria of papers that describe learning environments designed for neurotypical populations, which address knowledge acquisition as the primary goal and that are based on Full-body Interaction. Theoretical papers and studies on other forms of embodied interaction, robotics and construction kits were excluded.

Finally, we have included a total of thirty papers published between 2003 and 2013 (see Table 1). Since research in FUBILE is an emerging field, the chronological distribution of publications is strongly skewed toward recent years, with twenty-one papers being published between 2011 and 2013 and only ten published between 2003 and 2011. Also, as a consequence of the novelty of the field, most papers proceed from international conferences mainly dedicated to HCI or Learning Science. Only five of the reviewed papers proceed from journals and three are book chapters.

We oriented the analysis toward providing an exhaustive panorama of FUBILEs to offer a clear systematization of theoretical frameworks, design strategies and evaluation methods. For this purpose, the review focuses on the following aspects: the underlying theoretical frameworks; the design methodologies used; the interaction design choices; the evaluation methods applied; and the outcomes of the empirical analysis.

We used content analysis to classify the defined research topics into categories. Our coding procedure was realized through Nvivo software and comprised a blend of *a priori* categories with new categories emerging from a grounded analysis.

Table 1. Reviewed papers

	Project	Theoretical Framework			Design Strategy			Educational Context		Interaction Design		Evaluation		
		Dev Psych	Em Cogn	Phy	Semant	Adap	Phy	Content	Users	N° of users	Mapping	Learn	Comp study	UX
(Adachi et al., 2013)	Human Sugoroku	X				X		Science	Children	M	Functional		X	X
(Anastopoulou et al., 2011)	Kinematics graphic	X			X			Physics	Adults	S	Identity	X	X	
(Antle et al., 2008)	SoundMaker	X	X		X			Music	Children	M	Metaphor		X	X
(Antle et al., 2013)	SpringBoard		X		X			Social	Adults	S	Metaphor		X	X
(Carreras & Parés, 2009)	(Carreras & Parés, 2009)				X			Science	Children	M	Metaphor	X		X
(Charoenying et al., 2012)	(Charoenying et al., 2012)	X	X	X	X			Math	Children	M	Identity			X
(Cress et al., 2010)	(Cress et al., 2010)	X	X		X			Math	Children	S	Identity	X	X	
(Edge et al., 2013)	(Edge et al., 2013)	X	X			X		Language	Adults	S	n.d.	X	X	
SpatialEase	SpatialEase	X	X		X			Physics	Children	M	Identity	X		
(Grønbæk et al., 2007)	(Grønbæk et al., 2007)	X				X		Various	Children	M	Functional			
IGameFloor (StepStones)	IGameFloor (StepStones)	X	X					Math	Children	S	Functional	X	X	
(Hashagen et	(Hashagen et	X	X			X		Music	Adults	M	Metaphor			

al., 2009)	al., 2009)													
Der swarm	Der swarm	X	X		X	X		Music	Adults	M	Metaphor			
(Holland et al.,	(Holland et	X	X		X			Math	Children	S	Identity	X		
2009)	al., 2009)													
Song Walker	Song Walker	X	X		n.d			Science	Children	M	Functional	n.d.		
Harmony	Harmony													
Space	Space													
(Johnson-	(Johnson-	X	X		n.d			Science	Teens	M	Functional	X	X	X
glenberg et al.	glenberg et al.													
2011)	2011)													
Disease	Disease	X	X		X			Physics	Children	M	Identity			X
Outbreak	Outbreak													
(Johnson-	(Johnson-	X	X					Science	Teens	M	Functional	X	X	X
glenberg at al.,	glenberg at al.,													
2011b)	2011b)													
PUSH	PUSH	X	X					Physics	Adults	S	Identity	X	X	X
(Johnson-	(Johnson-			X			X	Various	Children	S	Functional	n.d.		
glenberg et al.,	glenberg et al.,													
2010)	2010)													
Layer Cake	Layer Cake		X					Physics	Children	M	Identity	X		X
Scenario	Scenario													
(Lee et al.,	(Lee et al.,	X	X		X			Language	Adults	S	Identity			X
2012)	2012)													
Live your life	Live your life	X		X				Social	Teens	M	Functional	X		X
in English	in English													
(Lim et al.,	(Lim et al.,		X		X			Physics	Children	S	Identity	X	X	
2011)	2011)													
ORIENT	ORIENT	X		X		X		Various	Children	M	Functional	X	X	X
(Lyons et al.,	(Lyons et al.,			X	X		X	Social	Children	M	Metaphor	n.d.		
2012)	2012)													
Climate	Climate	X	X		X			Physics	Children	M	Identity	X	X	X
change	change													
installation	installation													
(Malinverni et	(Malinverni et				X	X		Social	Children	M	Metaphor	n.d.		
al., 2012)	al., 2012)													
Arquimedes	Arquimedes		X					Physics	Teens	M	n.d.	n.d.		
(Pares et al.,	(Pares et al.,	n.d.			n.d			Music	Children	S	Metaphor	n.d.		
2005)	2005)													

The theoretical framework

Research in FUBILEs is mainly grounded on the benefits that physicality may provide to facilitate learning and enhance user experience. This idea is supported by different theoretical frameworks, which range from pedagogy to cognitive science and physiology. From our analysis, we identified three main approaches: (1) based on developmental psychology and pedagogical theories, (2) relying on Embodied Cognition and (3) based on the physiological benefits that exertion can bring to cognition. To situate the reviewed projects, we provide an overview of the main theoretical frameworks. Despite these approaches are interrelated, we describe them as separate sections for the sake of clarity.

The developmental psychology framework

From a pedagogical perspective FUBILEs are mainly based on constructivist and constructionist frameworks. The central pedagogical value is posed on the idea of learning-by-doing, understood as the fundamental role of hands-on activities and active experiences in the learning process.

The works of Jean Piaget, Seymour Papert and Jerome Bruner support such theoretical approach. Even when these authors have different perspectives on child development, they all agree that knowledge emerges as a result of people's action-in-the-world (Ackermann, 2001). Such perspective supports the action-oriented approach of Full-body Interaction and suggests its potential for facilitating the construction of knowledge through the internalization of actions.

A particular relevance is given to Piaget's notion of *schemata*, Papert's notion of *body-syntonicity* and Bruner's concept of *enactive representation*. Piaget suggests that the cognitive structuring of children is partially based on the extension of physical *schemata*, which represent internalized patterns of activity that are then used for thinking (Antle et al.,2008). Papert (1980), through the notion of *body-syntonicity*, describes instructional designs based on using children's knowledge about their own bodies to stress the 'resonance' between abstract concepts and what people know about themselves (Watt, 1998). Finally Bruner's theory about modes of representation of knowledge suggests that providing learners with different ways of thinking (enactive, iconic, symbolic) can facilitate the learning process (Di Paolo et al., 1991).

The embodied cognition framework

Twenty-one papers base their designs on the Embodied Cognition framework. Embodied Cognition has its philosophical roots in Merleau-Ponty who, by defeating Cartesian dualism, re-introduces the body as a skilled subjectivity that helps knowledge construction (Shusterman, 2013). Such framework emerged in cognitive science around fifty years ago and has been incorporated in HCI during the last two decades (Antle, 2013). According to this framework, almost all cognitive processes are influenced by physical states, bodily structures (Wilson, 2002) and experiential opportunities.

Embodied Cognition, by focusing on the fundamental role of action and perception in shaping cognitive processes, coherently relates with the pedagogical approach of learning-by-doing and provides a scientific ground for defining design strategies for FUBILEs. With this context, particular relevance is given to Barsalou's Grounded Cognition approach, Johnson and Lakoff's theory on the embodied nature of linguistic concepts, and to the studies on the relation between gesture and thought.

Barsalou's Grounded Cognition suggests that mental representations are grounded in motor areas of the cortex: when knowledge is needed, the perceptual and motor states acquired during experience are reactivated through simulation (Barsalou, 2008). The findings of Lakoff and Gallese support this hypothesis suggesting that the formation of linguistic concepts meet its bases in the sensorimotor system (Gallese & Lakoff, 2005). Similarly, Johnson proposes the Embodied Metaphor Theory, which suggests that abstract concepts and conceptual metaphors are based on image schemas that derive from physical actions (Johnson, 1987). Finally, the studies carried out by Goldin-Meadow (2011) show the intertwined relation existing between gestures, language and learning outcomes and propose instructional models capable of taking into account the role of body in thinking processes. According to her research, gestures can predict and provoke learning by displaying knowledge that cannot be expressed verbally yet and by facilitating knowledge construction.

The physiological framework

The third theoretical approach is related to the impact of physical activity on cognitive functioning, memory, attention allocation and academic performance (Castelli et al., 2007; Hillman et al., 2008). Recent researches show that aerobic exercise can improve several aspects of cognition, suggesting a physiological relation between physical activity and academic success. However, despite the raising importance of studies relating physical activity with academic success (Raine et al., 2013) it is interesting to notice that only three of the reviewed papers encompass such aspect in their design framework.

Design strategies

The overview of the theoretical frameworks shows that research in FUBILEs is based on findings that are consistent with research in developmental psychology, cognitive science and physiology. Developmental psychology and Embodied Cognition, by stressing the tight relation between body and knowledge construction, suggest the possibility of using relevant bodily actions to facilitate the grounding of abstract concepts. The studies on the physiological effects of exertion suggest that FUBILEs can be beneficial from a perspective that encompasses also the cognitive process at the very ground of learning such as memory and attention.

However, since HCI is an applied science it is necessary to analyze how these findings can be used to inform design. Such task represents a challenging requirement that implies concretizing complex theoretical frameworks into specific instances. To observe of how this challenge has been addressed, the following sections describe the most relevant design strategies and their relation with the underlying theoretical frameworks.

Only three papers use a design method that involves stakeholders or end-users in the design process (Enyedy et al., 2012; Grønbæk et al., 2007; Johnson-glenberg et al., 2010). Namely two of them are based on the collaboration with teachers (Enyedy et al., 2012; Johnson-glenberg et al., 2010) and one involves both teachers and children through the use of participatory design methods (Grønbæk et al., 2007). The rest of projects mainly arise from a perspective grounded on exploring theoretical constructs that, in some cases, are combined with empirical validation through user testing.

In this context three main design strategies were identified: a *semantic* approach, an approach based on the *adaptation of existing materials* and a *physiology-oriented* approach.

The semantic approach

Most analyzed projects rely on a semantic approach. This implies a design strategy oriented toward using the actions, events and activities of FUBILE as a reference for constructing meaning. This approach is generally aimed toward facilitating an embodied experience of a certain concept or toward representing an abstract concept as a concrete instance. From a theoretical perspective it is related to projects based on the Embodied Cognition framework.

Within this context, different semiotic resources, understood as “resources for making meaning” (Van Leeuwen, 2004) have been utilized to communicate the target contents. The greatest relevance is given to the role of actions as a vehicle to transmit meaning. Examples can be found in the Method for Meaning Generation proposed by Carreras & Pares (2009) and in the Embodied Metaphor Approach used by Antle (2013) and Holland (2011).

The *Method for Meaning Generation* focuses on operationalizing actions in terms of *attitudes* that we want the users to adopt and concentrates the design strategy on defining how the user will physically interact with the system. Examples can be found in “Connections” (Carreras & Pares, 2009) and “WaterGames” (Pares et al., 2005) where the values related to certain behavior (e.g., users hold hands with each other) serves as a link to express a specific concept (e.g., collaboration between scientists).

The *Embodied Metaphor Approach* proposes the use of Johnson’s theory of conceptual metaphor (1987) to inform design. An example can be found in “Springboard”, where the concept of “the balance of social justice” is derived from the physical experience of balancing our own bodies (Antle et al., 2013). Other examples are “Song Walker Harmony Space” and “Sound Maker” where embodied metaphors are applied to musical concepts (Holland et al., 2011).

Similarly to *actions*, another semiotic resource is *space*. An example can be found in Cress et al. (2010) where the spatial format supports children’s understanding of numerical comparison through the use of spatial cues (e.g., left = smaller, right = bigger). At the same time, the three projects based on Johnson’s Embodied Metaphors, use both physical and spatial metaphors as resources in their design. Interestingly, Antle (2008) points out that in “Sound Maker” children tended to use more spatial elements than bodily-based elements as sources for meaning-making. Another project based on the features of space is “Arquimedes” (Malinverni et al., 2012), where the physical affordances of the interface are used to communicate meaning. The project, based on the use of a large inflatable slide, employs the gravity experienced on the sliding surface to communicate concepts related to gravity itself.

Other projects propose the *coupling between physical movement and computational feedback* as the main semiotic resource for meaning-making (Anastopoulou et al., 2011; Charoenying et al., 2012). Both projects focus on the learning of graphical representations of mathematical and physical concepts and stress the role of mapping between changes in the user's movements and changes in graphs as the mediator of learning. For example "Bar Graph Bouncer" (Charoenying et al., 2012) couples the number of jumps performed by children with bar graph representations of quantities.

Finally, the project "PUSH" (Johnson-glenberg et al., 2011) and "Climate change" (Lyons et al., 2012) use the notion of effort as a semiotic resource. The former project uses the effort experimented by children while pushing virtual objects to address concepts of Newtonian forces. The latter uses the notion of effort to allow children understand the severity of climate change.

Adapting existing materials

Eight projects have a design strategy based on adapting existing materials to Full-body Interaction. Different strategies have been identified: (1) the adaptation of already existing applications, (2) the inspiration from traditional physical games and (3) the adaptation of educational material.

The project "Human Soguroku" adapts an already existing application designed for a desktop computer to Full-body Interaction for making the experience *more immersive* (Adachi et al., 2013). The project "SpatialEase," instead draws inspiration from an existing application and from the traditional physical game of "Simon says" (Edge et al., 2013).

The use of traditional games for developing FUBILEs finds examples in the projects "IGameFloor" (Grønbæk et al., 2007), "HOPSCOTCH" (Lucht & Steffi, 2013) and "WaterGames" (Pares et al., 2005). In "IGameFloor" and "HOPSCOTCH" the mechanics of the traditional games "Twister" and "hopscotch" are used in didactic exercises. Quite differently "WaterGames", instead of embedding novel content into already existing gameplay, looks for an existing game that shares a conceptual affinity with the addressed topic and therefore works as a semantic reference (e.g., "Ring-a-ring Roses" associated to "respect for diversity") (Pares et al., 2005).

Finally, the project proposed by Lee (2012), adapts the educational material of "Live your life in English" to a FUBILE to instill the naturalistic approach of English conversations and provide a context for *authentic learning*.

No explicit relation has been identified between a specific theoretical framework and these design strategies. Adapting existing materials can have its pros and cons. On one hand, it facilitates understanding through the use of culturally established models. On the other, especially in those cases based on adapting existing desktop applications, it could run the risk of reducing the potential of Full-body Interaction to that of merely emulating mouse-based interaction paradigms with the body as a large-scale pointing device.

Physiology oriented approach

Two papers propose a design strategy based on a physiological approach and design interaction according to the relation between physical and cognitive workloads (Kiili et al., 2012; Lyons et al., 2012). This approach correlates with studies on the impact of physical activity on cognitive functioning, memory and academic performance. Such strategy focuses on analyzing the tight relation between physical arousal, attention and memory formation. It therefore suggests the necessity of balancing the physical workload with the cognitive load and proposes designs aimed toward offering an amount of physical activity that is beneficial for learning processes.

The educational context

Learning goals

Eighteen projects refer to STEM topics: seven refer to mathematics, seven to physics and four to science. This predominance can be associated with the governmental efforts to foster STEM and with the affordances provided by Full-body Interaction. Studies on mathematical cognition suggest the embodied and spatial nature of mathematical concepts (Lakoff & Núñez, 2000), and several studies suggest a correlation between spatial thinking skills and STEM academic performance (Newcombe, 2010).

Four projects focus on learning abstract musical concepts and three on learning a second language. Projects that address learning musical concepts (Antle et al., 2008; Holland et al., 2011; Volpe et al.,2012) arise from the idea of using physicality and spatiality to provide a concrete experience of abstract concepts such tonal harmony. Projects about language learning arise either from the necessity of providing *authentic learning* experiences to the users (Lee et al., 2012) or from already existing instructional methods such as the *Total Physical Response*, which addresses second language learning through the co-production of spoken commands with bodily action (Edge et al., 2013).

Five of the analyzed projects focus on social sciences and particularly on topics that require a moral engagement such as social justice (Antle et al., 2013), environmental issues (Lyons et al., 2012), cultural diversity (Lim et al., 2011) or respect for diversity (Pares et al., 2005). The selection of these topics find their rationale in the capacity of direct experience to foster emotional arousal, suggesting the hypothesis that FUBILE could be capable of producing a higher impact, evoking empathy and producing behavioral changes.

Finally, three projects are not designed for a specific learning goal but work as frameworks where different contents can be implemented (Grønbæk et al., 2007; Kiili et al., 2012; Lucht & Steffi, 2013). Such a general approach correlates with the adoption of the theoretical framework based on the physiological benefits of exertion.

According to the revised version of Bloom’s taxonomy, learning goals can be structured into four classes of knowledge: *factual knowledge* (recall of elements), *conceptual knowledge* (knowledge of the core concepts), *procedural knowledge (*applied knowledge about “how to” do something) and *metacognitive knowledge* (knowledge about one's own cognition) (Krathwohl, 2002). Regarding these classes, projects based on frameworks where different contents can be implemented mainly address factual knowledge through didactic exercises (e.g., select the right answer). Instead, projects grounded on Embodied Cognition mainly address conceptual and procedural knowledge.

Target users

Out of the thirty projects, twenty are designed for children, four for teenagers and seven for adults. In projects designed for children the target age ranges from preschoolers (Cress et al., 2010) to primary school, with a high predominance of children between 10 and 12 years old. A possible explanation of this distribution can be found in children’s developmental trajectory; i.e., children around 11 years old are in a stage in which they start to think abstractly, reason about hypothetical problems (Perinat & Lalueza, 2007) and have well developed motor capabilities.

Context of use

Twelve projects arise from laboratory research and are tested in experimental settings. Other twelve are designed to be embedded in a school environment. Five are for museum spaces and one for a public space. The difference between settings has a fundamental role in defining design requirements, determining the educational experience and the empirical evaluation. This is clearly seen by comparing the educational experiences in an experimental setting or in a school environment. In most projects tested in the laboratory, participants use the system once for a limited amount of time and without any other educational support. Instead, in projects such as “Learning Physics” *(*Enyedy et al., 2012) the system is embedded in a complete educational program lasting fifteen weeks.

Interaction design

Physical configuration

Due to the physical and spatial nature of FUBILEs, a first aspect to consider is the configuration of the physical interface. Most projects are based on audiovisual outputs that combine visual representations and audio effects. Twenty-nine are mainly visual, while one uses only audio output (Antle et al., 2008).

In seventeen projects the physical interface is based on the use of vertical screens or wall projections, requiring users to interact in the space in front of the display. Within this configuration few differential elements are present, such as adding interactive sensors in the adjacent space (Holland et al., 2011; Lucht & Steffi, 2013; Lyons et al., 2012). On the other hand, twelve projects are based on floor projections, which allow the user to move around the periphery of or directly on the visual output (Carreras & Pares, 2009; Cress et al., 2010; Grønbæk et al., 2007; Hashagen et al., 2009; Johnson-glenberg et al., 2010; Lindgren & Moshell, 2013).

Interestingly, only two projects present a substantial difference in the physical interface: "Arquimedes" (Malinverni et al.,2012) and "WaterGames" (Pares et al., 2005). In "Arquimedes", the physical interface is a large inflatable slide, with a virtual environment projected on the sliding surface. In "WaterGames", the physical interface is a group of water fountains, where the output is constituted by water springs.

The homogeneity in the physical interfaces should provoke a reflection on the affordances of displays such as vertical screens and floor projections and suggest possible paths for innovation.

Single user or multiple users

Eleven projects are designed for a single user, whereas nineteen are designed for multiple users. In the latter case, the number of users that can simultaneously use the system ranges from a minimum of two to a maximum of twelve, with most projects addressing a number between three and five. A possible reason arises from the studies on group productivity, which indicate higher benefits when working in small groups (Mc Grath, 1984) .

In multi-user systems it is relevant to look at how different patterns of group interaction are implemented since specific design choices can generate interactions that are beneficial for learning outcomes (Dillenbourg et al., 2009). Except for the "Climate change" project (Lyons et al., 2012) and "Bar Graph Bouncer" (Charoenying et al., 2012), based on the competition between two users, all other projects are oriented toward collaboration. For example, "Feed yer Alien" distributes different roles among the users: one chooses the correct food and the other brings it to the alien (Johnson-glenberg et al., 2012). Such design generates interdependencies among tasks and consequently facilitates discussion and shared decision-making. Instead projects such as "Archimedes" (Malinverni et al., 2012) and "Wooble" (Kynigos et al., 2010), do not differentiate between users and assign the same role to all of them. However, relevant differences are present: in "Arquimedes" each child acts as an individual entity, whereas in "Wooble" children have to behave as a homogenous entity by coordinating their collective displacement.

Although analyzing the relation between group interaction and learning is not the purpose of this paper, it is necessary to consider the definition of different patterns of collaboration as a fundamental design choice since it can be used both to convey meaning and to facilitate social interactions which are beneficial for learning.

Input technologies and operationalization of user behavior

Social sciences suggest that the notion of *body* depends on how we look at it (Thomas, 2003). This concept, applied to HCI, requires analyzing how the system conceptualizes the user's body and his behavior. According to Fogtmann et al. (2008), interaction with a system always imposes constraints on how the body is involved in this interaction. This is due to the choice of different sensing devices which offer diverse understandings of the interacting body.

Two main approaches are used to sense the interacting body: either a "sensor-activation" approach or a "motion tracking" approach. Within the former context different commercial devices are used (e.g., DanceMat, Wiimote, smart phone’s accelerometer), while motion tracking approaches are based on specifically developed artificial vision systems, Kinect devices or laser scanning. Despite differences in the sensing systems used, most projects are based on tracking body or limbs position in space, with some of them integrating also data on the quality of movements (i.e., speed, flow, time, etc.).

Other projects propose different operationalization of user behavior such as: tracking gestures, the quantity of movement or the collective behavior of multiple users. Examples of this last approach can be found in “Wobble” and “Watergames.” In “Wobble” players control a virtual board through their collective displacement on the floor: the system recognizes the total weight of players and its distribution and operationalizes the interaction in terms of coordinated movement and proximity between users (Kynigos et al., 2010). In “Watergames” the system reacts and activates a fountain only when a group of children creates a closed ring and spins around the fountain (Pares et al., 2005).

These examples, by showing different forms of conceptualizing users, suggest that the definition of the input represents a fundamental starting point. This is because it directly affects the mental models of users on how they can interact with the system and defines possibilities for meaning construction. The definition of the sensing technology does not only represent a technological choice but can feed knowledge construction by operationalizing user behavior in a meaningful way.

Mapping

The concept of mapping, defined by Norman (1988) as the relation between “*controls and their movements and results in the world*”, has been present for many years in HCI. While in its general definition mapping provides a strategy to make an interface easy to use, within FUBILEs a further layer of complexity is added since users do not only have to understand how the systems works but also must understand the target learning goals (Fig. 1).

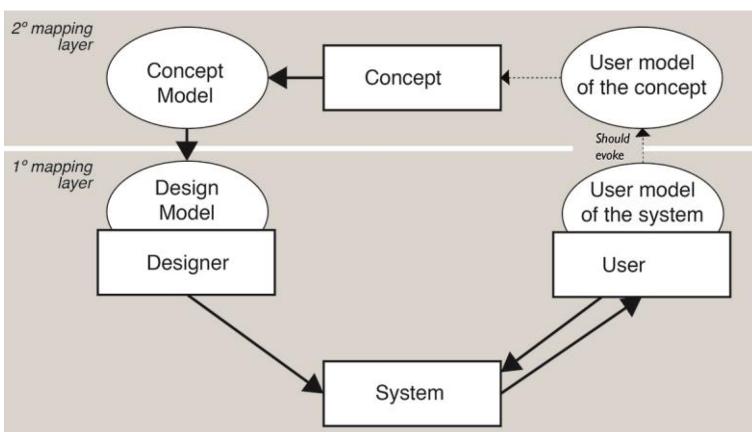

Figure 1. Multi-layered mapping. Users need to understand the system (first layer) and mapping should support the understanding of the content (second layer)

A first aspect to analyze is whether mapping and user actions are related to the defined learning goal and how they related. Three main approaches were identified: a “functional” approach, an “identity” approach and a “metaphorical” approach.

The “functional” approach represents the cases in which user actions and mapping do not relate with the content but arise from a usability perspective. Examples can be found in (Grønbæk et al., 2007; M. C. Johnson-glenberg et al., 2010; Kiili et al., 2012; Lim et al., 2011; Lucht & Steffi, 2013), which mainly rely to the application of traditional interaction paradigms of mouse-based interaction (i.e., select, drag, drop). The majority of these projects arise either from a technologically oriented framework or from approaches related to exertion and to the adaptation of existing materials.

On the other hand, both the “identity” and the “metaphorical” approaches are oriented toward establishing a relation between user actions and content. Based on the Embodied Cognition framework and on a semantic design, these projects focus on designing actions that allow having a physical experience of the concept taking advantage of body knowledge.

The identity approach orients the mapping toward creating tight *analogies* between user action and content. For instance “Magic Angle,” which aims at the learning of methods to measure angles, requires children to physically enact angles with their arms (Liu et al.,2006). Similarly “Kinematics graphic” (Anastopoulou et al., 2011) maps the arm movement to graph of the relation between velocity, time and distance. Finally “Meteor” (Lindgren & Moshell, 2013) and “Archimedes” (Malinverni et al., 2012) require children to physically perform the behavior of specific virtual objects. From a semantic perspective the identity approach works as a denotative meaning, understood as using the literal meaning of user actions to indicate the concepts.

However, as Holland et al. (2011) pointed out, some concepts cannot be expressed through the literal meaning of body actions. To address this issue the “metaphorical” approach proposes a mapping strategy based on defining metaphors to bond users actions with the content. In these cases user action does not correspond to its literal meaning but works as a symbol for something else; e.g., (Antle et al., 2013, 2008; Carreras & Pares, 2009; Holland et al., 2011; Lyons et al., 2012; Pares et al., 2005). For instance, the project “SpringBoard” uses Johnson’s Embodied Metaphor of balance to map the proprioceptive experience of balancing our own body onto the concept of social justice. The use of a metaphor offers strategies to address abstract concepts that cannot be physically enacted in a literal way; however it is necessary to reflect on whether the multiple layers of meaning of metaphors can facilitate the understanding or add an additional level of complexity in the learning process. For metaphors to be correctly understood, they need to be based on strongly shared socio-cultural references. This is often difficult to guarantee, especially in projects addressed to children.

Table 2. Interaction design

	Features	Number of projects	
Physical configuration	Vertical screen / projection	17	
	Floor projection	12	
	Other	2	
Number of users	Single users	11	
	Multiple users	Competitive	2
		Collaborative	17
Input data	Body/limb position	17	
	Quality of movement	3	
	Quantity of movement	3	
	Gestures	2	
	Collective behavior of multiple users	3	
Mapping	Functional	8	
	Identity function	9	
	Metaphorical	6	

Evaluation

Twenty-one papers report empirical studies for evaluating the impact on learning and user experience. Sixteen of them focus on assessing learning outcomes, while five are oriented toward evaluating user experience. In all cases an effort is posed on evaluating the specificities of Full-body Interaction by comparing it with other instructional methods or with traditional interfaces.

Evaluating learning

Papers aimed at assessing the impact on learning are mainly based on the administration of retrospective measures, understood as evaluating learning through the administration of tests after the experience. Two main approaches are used: three studies use only post-task assessment, while eleven use an experimental design based on pre and post test. Both single measure and repeated measures have pros and cons: the latter can increase the risk of repetition biases while the former makes it difficult to properly track learning gains.

Only Cress et al. (2010) use data logs of the performance to evaluate learning. In their study on using the DanceMat to foster numerical skills in children, they analyze data logs to assess improvements in accuracy and performance time between the first and second use of the application. Data logging can provide highly reliable quantitative data, however its application for complex learning goals can be challenging.

In terms of assessment instruments nine projects are based on multiple-choice questionnaires, three on interviews and three on mixed methods that combine interviews, questionnaires and discussion. This distribution requires a reflection on the relation between theoretical frameworks and assessment instruments. Most projects rely on constructivism but utilize instruments such as multiple-choice questionnaires. This does not seem coherent since questionnaires are often criticized by constructivism itself due to their deficiencies in properly discriminating the reasoning process behind the answers (Berg & Smith, 1994) and in evaluating understanding at a deeper level (Reeves & Okey, 1996). This contradiction requires further research on evaluation methods for FUBILEs, since only one project explicitly includes the tracking of the learning process and a deep analysis of students' understanding (Howison et al., 2011).

At the same time retrospective assessment is partially contradictory with the very nature of FUBILEs and embodied learning. Recent studies suggest that implicit bodily-based knowledge may precede the ability of children to properly articulate verbally their understanding (Broaders & Goldin-Meadow, 2010). Such aspect suggests the necessity of considering the role of bodily-based knowledge and overcoming the limits of verbal expression in the assessment of FUBILE.

The assessment of full-body interaction: Comparing interfaces

Ten out of fifteen papers aimed at assessing learning report studies that evaluate the specific potential of Full-body Interaction by comparing it with other interfaces or instructional methods. Such studies are based on experimental designs where users are assigned either to a Full-body Interaction condition or to a control condition.

Relevant differences are present in the control condition. Four studies compare the use of the same application with two different interfaces; e.g., in "Arquimedes", the same application is used either on a large inflatable slide or on a desktop computer (Malinverni et al.,2012). Two papers compare their system with a different desktop application, i.e., "SpatialEase" compare a FUBILE for learning second language with an already existing desktop application that has the same learning goals (Edge et al., 2013). Finally four papers compare the interactive experience with other instructional methods, such as traditional classroom instructions.

Despite the diversity in their research question, all comparative studies evaluate whether there is a significant difference between two conditions (i.e., whether an interaction modality is more effective than another) but none of them consider the qualitative aspects related to how users can learn differently depending on the interface. Such limitation has been already discussed by Kozma (1994) who suggested deepening the research on the effects of media on learning through the use of more qualitative approaches.

Results

Results of learning outcomes and comparative studies report a heterogeneous panorama. Despite fifteen papers evaluate learning, only fourteen clearly report their results: nine report significant improvements in learning, while five did not find any significant learning gains.

Comparative studies between Full-body Interaction and traditional instructional methods report significant differences in learning gains for the users assigned to the FUBILE condition. Comparative studies between FUBILE and desktop interfaces show no significant difference in five out of six projects. Only Cress et al. (2010) who compared a numerical task on DanceMat and on a tablet computer reported a significant difference in favor of users of the FUBILE.

The broad diversity in learning goals, design strategies and assessment methods makes it difficult to extrapolate consistent conclusions about these findings, however some aspects can be considered to provide guidelines for research and design. The projects that reported significant learning gains addressed learning goals that are clearly operationalized, while most studies that did not report significant gains deal with much more diffuse topics. For instance "Arquimedes", which reported significant learning gains, focused its learning goal on Archimedes principle (Malinverni et al., 2012); conversely "Wooble", which did not report any learning gain, addresses goals related to "force, balance, weight, location, direction" (Kynigos et al., 2010). Despite several factors could contribute to the effectiveness of a FUBILE, it could be beneficial to clearly delimitate learning goals to circumscribe the amount of information that we want to communicate to the user. The results of "Wobble" are particularly indicative. After using the system, users were asked to define its educational content and none of them related it with physics. This misunderstanding suggests the necessity of carefully evaluating the communicative and interpretative aspects of design.

Studies on the comparison with traditional methods confirm the literature on the benefits of learning by doing and the role of active experience in grounding concepts. On the other hand, studies on the effect of the interactional difference posit much more challenging questions. As mentioned before, the study proposed by Cress et al. (2010) has two differential elements: (1) it is the only one that uses an evaluation method based on analyzing user performance and (2) it addresses the topic of numerical magnitude, which is deeply related to spatial and bodily cognition.

Even if it is not possible to disentangle these factors, novel research lines for FUBILEs could address the definition of proper learning goals and adequate assessment methods. Relevant shortcomings can found in a dichotomist approach (i.e., "is A more effective than B?"), which does not allow understanding in which aspects Full-body Interaction really differs from other kinds of interaction modalities.

Table 3. Summary of results

Evaluation		Significant difference	Non significant difference
Learning gains		(Cress et al., 2010; Edge et al., 2013; Enyedy et al. 2012; Howison et al., 2011; Johnson-glenberg et al., 2010, 2011b; Lucht & Steffi, 2013; Malinverni et al.,2012)	(Carreras & Pares, 2009; Hashagen et al., 2009; Kynigos et al., 2010; Lim et al., 2011)
Difference between conditions	Different interfaces	(Cress et al., 2010)	(Edge et al., 2013; Johnson-glenberg et al., 2010; Lindgren & Moshell, 2013; Malinverni et al., 2012)
	Different instructions	(Anastopoulou et al., 2011; M. C. Johnson-glenberg et al., 2010, 2011a; Lucht & Steffi, 2013)	

Evaluating user experience

Seven papers focus on evaluating user experience, while the other combines this evaluation with the assessment of learning. Different aspects are analyzed: the enjoyment of the experience, its impact on the user, the level of motivation, and changes in the attitude toward the learning goals. Methods include interviews, questionnaires and observations. Contrary to assessment of learning, results are highly homogeneous, reporting significant differences in engagement, immersion and motivation in all of the studies aimed at comparing user experience in Full-body Interaction with a traditional interface.

Such findings suggest that FUBILEs can be highly effective in emotionally involving the users and motivating them. Antle et al. (2013) and Lucht et al. (2013) report particularly relevant results. Antle reports a significant difference in awareness, impact and willingness to get involved with social justice between the users assigned to the FUBILE and those assigned to the control condition. Lucht shows that children trained with FUBILE report a significantly higher positive attitude toward English, when compared to those assigned to the traditional classroom condition.

Such findings are consistent with the research on physical activity and user's attitude (Bianchi-berthouze, 2013) and suggest considering the pedagogical potential of FUBILEs from a perspective that includes the affective aspects of learning. However, longitudinal studies become extremely necessary at this point to be able to compensate for the novelty factor.

Discussions

This review reports a panorama of the theoretical frameworks, design approaches and empirical evaluations of FUBILEs, identifying tendencies and shortcomings useful for future research. At the same time the structure of the analysis can serve as a framework for research by providing a "checklist" of critical aspects to consider when designing for FUBILEs (see Table 4).

Table 4. Design checklist

Educational context	- Definition of learning goals and learning process: *How are the learning goals selected? Is there any theoretical support for their relation with physicality? Do they address needs expressed by stakeholders? How are users supposed to learn?* - Definition of target users - Context: *How is the educational experience framed?*
Interaction design	- Physical interface: *Which physical interface will be used? Why? Which affordances does it support?* - Number of users: *How many users will be able to use simultaneously the system? Which patterns of group interaction are implemented? Which emergent social interactions can be provoked?* - Operationalization of user behavior: *which aspects of user behavior are used as inputs by the system? Do these aspects allow mapping with learning goals?* - Mapping: *Do the mapping of user activities relate with learning goals? How?*

Three major theoretical frameworks have been identified as bedrocks of research in FUBILEs: (1) a pedagogical framework, based on the importance of learning-by-doing; (2) an Embodied Cognition framework that scientifically grounds the fundamental role of the body in cognitive processes; (3) a physiology-oriented framework that suggests the tight relation between exertion and academic performance. These three theoretical frameworks are reflected in specific design strategies, which include the adaptation of existing materials, the balance between physical workload and cognitive load and the use of elements of the system to communicate meaning. Within this latter approach a number of semiotic resources have been identified: the design of user activity, the role of space, the coupling between physical movement and computational feedback, the notion of effort and the relations between multiple users.

At the same time the analysis of the design strategies showed that most of them are based on a theory-oriented approach, with only few examples including either users or stakeholders in the design process. Such tendency is partially unaligned with the emergent claim of HCI community about involving users at a deeper level. It suggests the need of researching on design methods capable of blending complex theoretical models with a user-centered approach. This need is even more evident in the cases in which the designer's goal is to communicate abstract concepts.

Future work

The analysis of specific design choices allowed formalizing a preliminary structure that can serve as guidelines for researchers and designers. The review of the physical interfaces, number of users, system inputs and mapping showed that these aspects are either designed to accomplish a functional purpose or to facilitate meaning construction. However, even when a design choice is mainly focused toward functionality, it is necessary to be aware of its communicative potential. This implies carefully analyzing the specific affordances, cultural constructs and behavioral effects that it can evoke.

Additional research is needed to properly take into account the broad amount of variables embedded in FUBILEs. Possible research paths can analyze the relation between design choices and the emergence of specific user behavior and affects. Studies in Tangible User Interaction and learning show that even subtle changes in the physical configuration of the environment can have relevant impact on comprehension (Price & Jewitt, 2013), pointing out the need of fine-grain analysis of the relation between design choices, behavior and cognitive processes.

This need is intertwined with the research on adequate evaluation methods. Evaluation methods should be aligned with the underlying theoretical frameworks, while at the same time be capable of offering a deeper understanding on the specific effects of Full-body Interaction on learning outcomes. Relevant possibilities can be found in overcoming the binary approach (i.e., "is A more effective than B?") to properly analyze which understanding and skills can be fostered through Full-body Interaction. Such approach pushes us towards searching for misconceptions, emerging representations and plotting different levels of learning outcomes. Interesting approaches can be found in combining methods such as Stealth Assessment (Shute, 2005) , which evaluates the skills of the learner during the interaction, with the analysis of embodied meaning construction. Finally, research should address the understanding of whether some kind of users can benefit more of a Full-body Interaction experience; e.g., initial low knowledge vs. initial high knowledge or different categories of learners.

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