Bridging the Physical Learning Divides: A Design Framework for Embodied Learning Games and Simulations

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ABSTRACT
Due to a broad conceptual usage of the term embodiment across a diverse variety of research domains, existing embodied learning games and simulations utilize a large breadth of design approaches that often result in seemingly unrelated systems. This becomes problematic when trying to critically evaluate the usage and effectiveness of embodiment within existing designs, as well as when trying to utilize embodiment in the design of new games and simulations. In this paper, we present our work on combining differing conceptual and design approaches for embodied learning systems into a unified design framework. We describe the creation process for the framework, explain its dimensions, and provide examples of its use. Our design framework will benefit educational game researchers by providing a unifying foundation for the description, categorization, and evaluation of designs for embodied learning games and simulations.

Keywords
Embodiment, Embodied Learning Games and Simulations, Design Framework

INTRODUCTION
Recent work on educational systems has shown the benefits of incorporating physicality, motion, and embodiment into designs. For instance, improved spatial recall and mental manipulation (Clifton, 2014; Rieser, Garing, & Young, 1994); more intuitive interfaces, interactions, and mappings (Shelley, Lyons, Zellner, & Minor, 2011; Wyeth, 2008); increased engagement (Bhattacharya, Gelsomini, Pérez-Fuster, Abowd, & Rozga, 2015; Edge, Cheng, & Whitney, 2013; Yannier, Koedinger, & Hudson, 2013); greater positive feelings towards learning content and science in general (Lindgren, Tscholl, & Moshell, 2013; Wei, Chen, & Chen, 2015; Yannier et al., 2013); and enhanced collaboration (Ahmet, Jonsson, Sumon, & Holmquist, 2011; S. Price, Rogers, Scaife, Stanton, & Neale,

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2003; Yannier et al., 2013). This direction stems from the concept that cognition does not only occur in the mind but is also supported by bodily activity (Shapiro, 2010); situated in and interacting with our physical and social environment (Clark, 2008; Dourish, 2001).

However, when examining existing embodied learning games and simulations closely, we find a large breadth of designs that result in seemingly unrelated systems (see Figure 1). This becomes problematic when trying to understand where and how embodiment occurs in these systems, and which design elements help to facilitate embodied learning. The problem is further aggravated by limited empirical validation of many systems (Zaman, Vanden Abeele, Markopoulos, & Marshall, 2012), and a broad conceptual usage of embodiment and related terms in a diverse variety of domains such as Human-Computer Interaction (HCI), learning science, neuroscience, linguistics, and philosophy (Birchfield et al., 2008; Rohrer, 2007; Ziemke, 2002). Therefore, for designers seeking to utilize embodiment (i.e., an emergent property from the interactions between brain, body, and the physical/social environment [Hummels & van Dijk, 2014]), the differences in approach to physicality, collaboration, and interaction pose a significant hurdle. One approach that can bridge conceptual differences between existing systems and domains is the creation of a design framework (Ens & Hincapié-ramos, 2014; Robinett, 1992).

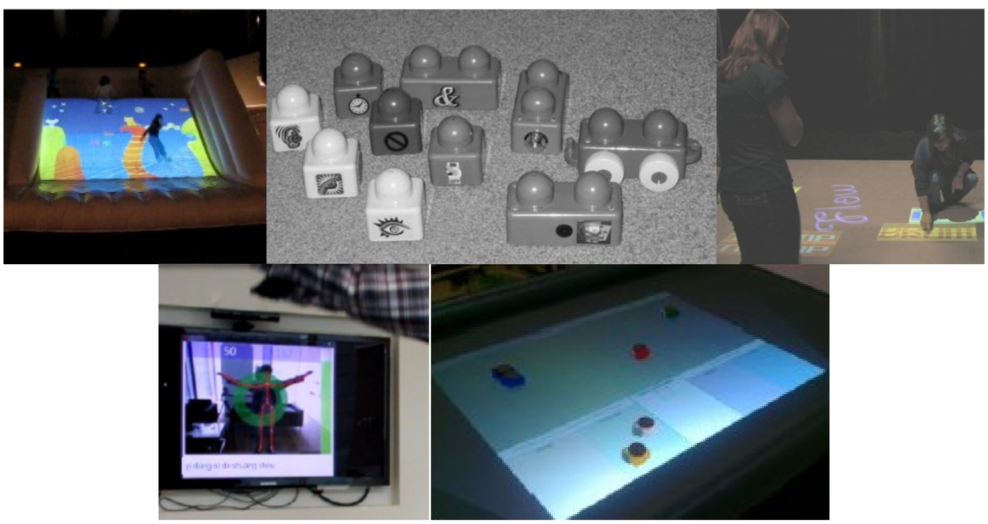

Figure 1: A spectrum of different embodied learning systems. Left to right - *Interactive Slide* (Malinverni, López Silva, & Parés, 2012), *Electronic Blocks* (Wyeth, 2008), *Embodied Poetry* (Kelliher et al., 2009), *SpatialEase* (Edge et al., 2013), *Eco Planner* (Esteves & Oakley, 2011).

BACKGROUND

Our goal in providing an embodied learning design framework is to bridge conceptual gaps and resulting design choices made from the differing uses of embodiment in various domains. In this section we present an overview of design frameworks, embodiment and its application in educational games and simulations, and embodied learning taxonomies.

Design Frameworks

Design frameworks can help designers conceptualize nuances of particular technologies and formalize the creative process (Ens & Hincapié-ramos, 2014). In interface design,

design frameworks have been used to provide terminology to categorize ideas (B. A. Price, Baecker, & Small, 1993) as well as organize complex concepts into logical hierarchies (Plaisant, Carr, & Shneiderman, 1995). Design frameworks are created by treating a set of taxonomical terms as orthogonal dimensions in a design space, and the resulting matrix provides structure for classification and comparison of designs (Robinett, 1992). The completed design framework provides a means to critically examine designs of existing systems and encourage new designs by providing a unifying foundation for the description and categorization of systems. Furthermore, the methodical filling-in of this structure helps to categorize existing concepts, differentiate ideas, and identify unexplored terrain (Ens & Hincapié-ramos, 2014).

Embodiment, Embodied Cognition, and Embodied Interaction in Educational Games and Simulations

Embodiment and related terms such as embodied cognition and embodied interaction have many different interpretations and applications across a wide range of academic domains. HCI tends to view embodiment from a phenomenological perspective where embodiment is a physical and social phenomena that unfolds in real time and space as a part of the world in which we are situated (Dourish, 2001). However, learning science views tend to be more oriented on purely the body as a central focus for embodiment (Johnson-Glenberg, Birchfield, Tolentino, & Koziupa, 2014; Rohrer, 2007). Moreover, Ziemke (2002) has noted this divide in their work identifying six different uses of embodiment across research domains (i.e., structural coupling, historical embodiment, physical embodiment, organismoid embodiment, organismic embodiment, and social embodiment). In order to encompass a large corpus of embodied designs in our design framework, we take a broad perspective of embodiment: centering it around the notion that human reasoning and behavior is connected to, or influenced by our bodies and their physical/social experience and interaction with the world (S. Price & Jewitt, 2013). This is seen as an iterative relationship, where reasoning and behavior can shape interaction as well as the other way round, yet also complex because of the context, time, space, emotion, etc. in which interaction is situated.

Embodied cognition is a similarly important but divided term for education, with Wilson (2002) identifying six distinct views of embodied cognition where 1) cognition is situated; 2) cognition is time-pressured; 3) we off-load cognitive work onto the environment; 4) the environment is part of the cognitive system; 5) cognition is for action; and 6) off-line cognition is body-based. In learning science, embodied cognition considers how human cognition is fundamentally grounded in sensory-motor processes and in our body's internal states (Ionescu & Vasc, 2014). As a result of this body-centric perspective, learning science games and simulations explicitly addressing embodied cognition tend to focus on the utilization of sensors to map full-body interaction and congruency to learning content through the use of gestures (Barendregt & Lindström, 2012; Howison, Trninic, Reinholz, & Abrahamson, 2011; Johnson-Glenberg et al., 2014), or to track whole-body enactment of learning material (Hatton, Campana, Danielescu, & Birchfield, 2009; Lindgren et al., 2013). Conversely, HCI and subdomains such as Tangible Embodied Interaction (TEI) view embodied cognition from a body-in-action perspective where cognition is a coordination achieved through our brain, our body, and the dynamic relationships between our body and the physical- and social environment (Clark, 1997; Hummels & van Dijk, 2014). The resulting embodied cognition oriented games and simulations in HCI and TEI tend to focus on a more social and collaborative design, with sensors utilizing physical action as input into virtual or mixed reality worlds (Clifton, 2014; Mickelson & Ju, 2011; Nakayama et al., 2014).

Embodied interaction is a term coined by Dourish (2001) to capture a number of research trends and ideas in HCI around tangible computing, social computing, and ubiquitous computing. It refers to the creation, manipulation, and sharing of meaning through engaged interaction with artifacts (Dourish, 2001), and includes material objects and environments in the process of meaning making and action formation (Streeck, Goodwin, & LeBaron, 2011). Games and simulations utilizing embodied interaction tend to place the player in a physical space where they can physically manipulate interactive tangible tabletops, blocks, and objects (Bakker, Hoven, & Antle, 2011; Chu, Clifton, Harley, Pavao, & Mazalek, 2015; Esteves & Oakley, 2011; Rikić, 2013).

Embodied Learning Taxonomies

Similar to the many interpretations of embodiment, embodied learning frameworks and taxonomies also have vastly different interpretations of physicality, motion, collaboration, and interaction. Johnson-Glenberg et al (2014) created an embodied learning taxonomy that specifies the strength of embodiment as a combination of the amount of motoric engagement, gestural congruency to learning content, and immersion. Black et al (2012) created the Instructional Embodiment Framework (IEF) which consists of various forms of physical embodiment (i.e., direct, surrogate, and augmented) as well as imagined embodiment (i.e., explicit and implicit) where the individual can embody action and perception through imagination. In the TEI field, Fishkin's taxonomy (2004) for the analysis of tangible interfaces views embodiment as the distance between input and output where embodiment can be full (output device is input device), nearby (output is directly proximate to input device), environmental (output is "around" the user), or distant (output is on another screen or in another room). A related framework by Price (2008) for tangible learning environments focuses on different possible artifact-representation combinations and the role that they play in shaping cognition. The physical-digital links of these combinations are conceptualized into four distinct dimensions: location—the different location couplings between physical artifacts and digital representations; dynamics—the flow of information during interaction (e.g., is feedback immediate or delayed); correspondence—the degree to which the physical properties of objects are closely mapped to the learning concepts; and modality—different representation modalities in conjunction with artifact interaction.

TOWARDS A DESIGN FRAMEWORK FOR EMBODIED LEARNING GAMES AND SIMULATIONS

Creating the Design Framework

To create our design framework, we conducted an extensive literature review for published examples of embodied learning games and simulations in venues such as CHI, TEI, FDG, and Interaction Design and Children (IDC). Notably, the core nature of all games is embodied to some extent. Therefore, for the purpose of this research, only papers that explicitly mentioned embodiment or related terms (e.g., embodied learning, embodied cognition, embodied interaction, etc) were collected/used in the literature review. We also performed a tree search of references and citations from the initial papers collected and seminal papers concerning embodiment. In addition, we examined related frameworks and taxonomies in subdomains and communities such as TEI (Fishkin, 2004; O'Malley & Fraser, 2004; S. Price, 2008), embodiment and embodied learning (Black et al., 2012; Johnson-Glenberg et al., 2014), and mixed reality (Ens & Hincapié-ramos, 2014; Rogers, Scaife, Gabrielli, Smith, & Harris, 2002). Our final list contains papers describing designs for a total of 48 different embodied learning games and simulations (for the complete list of designs and their categorization within our design framework, go to: *http://edwardmelcer.net/research/supplementary_framework_table.pdf*). This list is not intended to be exhaustive, but does represent a diverse selection of designs that could be drawn upon when creating a design framework. Bottom up, open coding was then performed following the process described by Ens & Hincapié-ramos (2014) in order to distill a set of 25 candidate dimensions that fit concepts found in the reviewed literature and designs. Candidate dimensions were iteratively reduced and combined into a set small enough for a concise framework. Afterwards, we presented our framework to experts in HCI, game design, and learning science for feedback and additional refinements. The final design framework consists of 7 dimensions shown in Table 1. We further organized the dimensions into three groups based on their overarching design themes within the construct of embodiment (i.e., physical body and interactions, social interactions, and the world where interaction is situated).

<table>
<tr><th>Group</th><th>Dimension</th><th colspan="5">Values</th></tr>
<tr><td rowspan="4">Physical Interaction</td><td>Physicality</td><td>Embodied</td><td>Enacted</td><td>Manipulated</td><td>Surrogate</td><td>Augmented</td></tr>
<tr><td>Transforms</td><td>PPt</td><td colspan="2">PDt</td><td colspan="2">DPt</td></tr>
<tr><td>Mapping</td><td>Discrete</td><td colspan="2">Co-located</td><td colspan="2">Embedded</td></tr>
<tr><td>Correspondence</td><td colspan="2">Symbolic</td><td colspan="3">Literal</td></tr>
<tr><td rowspan="2">Social Interaction</td><td>Mode of Play</td><td>Individual</td><td colspan="2">Collaborative</td><td colspan="2">Competitive</td></tr>
<tr><td>Coordination</td><td>Other Player(s)</td><td colspan="2">NPC(s)</td><td colspan="2">None</td></tr>
<tr><td>World</td><td>Environment</td><td>Physical</td><td colspan="2">Mixed</td><td colspan="2">Virtual</td></tr>
</table>

Table 1: Our design framework for embodied learning systems. Similar dimensions are clustered under a group based on an overarching design theme, and the different values for each dimension are shown.

Design Space Dimensions

Physicality describes how learning is physically embodied in a system and consists of five distinct values. 1) The *embodied* value refers to an embodied cognition and learning science approach where the body plays the primary constituent role in cognition (Shapiro, 2010). This form of embodiment focuses on gestural congruency and how the body can physically represent learning concepts (Johnson-Glenberg et al., 2014). For instance, a full body interaction game where players contort their bodies to match letters shown on a screen (Paul, Goh, & Yap, 2015). 2) The *enacted* value refers to Direct Embodiment from the IEF (Black et al., 2012), and to enactivism which focuses on knowing as physically doing (Holton, 2010; Li, 2012). This form of embodiment focuses more on acting/enacting out knowledge through physical action of statements or sequences. For example, a gravitational physics game where payers walk along (i.e., enact) the trajectory an asteroid would travel in the vicinity of planets and their gravitational forces (Lindgren et al., 2013). 3) The *manipulated* value refers to the tangible embodied interactions of TEI (Marshall, Price, & Rogers, 2003) and the use of manipulatives in learning science

(Pouw, van Gog, & Paas, 2014). This form of embodiment arises from utilization of embodied metaphors and interactions with physical objects (Bakker, Antle, & van den Hoven, 2012), and the objects' physical embodiment of learning concepts (Ishii, 2008; S. Price, 2008). 4) The *surrogate* value refers to the IEF concept of Surrogate Embodiment, where learners manipulate a physical agent or "surrogate" representative of themselves to enact learning concepts (Black et al., 2012). This form of embodiment is often used in systems with an interactive physical environment that is directly tied to a real-time virtual simulation (Gnoli et al., 2014; Kuzuoka, Yamashita, Kato, Suzuki, & Kubota, 2014). 5) The *augmented* value refers to the IEF notion of Augmented Embodiment, where combined use of a representational system (e.g., avatar) and augmented feedback system (e.g., Microsoft Kinect and TV screen) embed the learner within an augmented reality system. This form of embodiment is most commonly found in systems where learners' physical actions are mapped as input to control digital avatars in virtual environments (Lyons, Silva, Moher, Pazmino, & Slattery, 2013; Nakayama et al., 2014).

Transforms conceptualize a space, describing the relationships between physical or digital actions and the resulting physical or digital effects in the environment (Rogers et al., 2002). We utilize the transform types of *Physical action => Physical effect* (PPt), *Physical action => Digital effect* (PDt), and *Digital action => Physical effect* (DPt) from Rogers et al (2002) to describe the many forms of existing systems.

Mapping borrows the notion of Embodiment from Fishkin's (2004) taxonomy and Location from Price's (2008) tangible learning environment framework which describes the different spatial locations of output in relation to the object or action triggering the effect (i.e., how is input spatially mapped to output). Mappings can be *discrete*—input and output are located separately (e.g., an action triggers output on a nearby screen); *co-located*—input and output are contiguous (e.g., an action triggers output that is directly adjacent or overlaid on the physical space); and *embedded*—input and output are embedded in the same object.

Correspondence builds upon the notion of Physical Correspondence from Price's (2008) tangible learning environment framework which refers to the degree to which the physical properties of objects are closely mapped to the learning concepts. We expand this concept to also include physical actions (e.g., congruency of gestures or physical manipulations to learning concepts). Correspondence can be *symbolic*—objects and actions act as common signifiers to the learning concepts (e.g., arranging programming blocks to learn coding); or *literal*—physical properties and actions are closely mapped to the learning concepts and metaphor of the domain (e.g., playing an augmented guitar to learn finger positioning).

Mode of Play specifies how individuals socially interact and play within a system. The system can facilitate *individual*, *collaborative*, or *competitive* play for learner(s). Plass et al (2013) found differing learning benefits for each mode of play, suggesting it is also an important dimension to consider for learning outcomes.

Coordination highlights how individuals in a system may have to socially coordinate their actions (Oullier, de Guzman, Jantzen, Lagarde, & Kelso, 2008) in order to successfully complete learning objectives. Social coordination can occur with *other players* and/or in a socio-collaborative experience with digital media typically in the form of *NPCs* (Tolentino, Savvides, & Birchfield, 2010). Conversely, social coordination can also be of limited focus in a design and not occur or even be supported.

Environment refers to the learning environment in which the educational content is situated. Environments can be either physical, mixed, or virtual (Rogers et al., 2002). While transforms conceptualize a space through the description of actions and effects, the environment dimension focuses on the actual space where learning occurs. For instance, a PDt transform can occur in drastically different learning environments (see Figure 2). In some systems, a player's physical actions are tracked but only used as input to control a virtual character in a virtual environment (Lyons et al., 2013). In other systems, the player's physical actions are tracked and mapped to control digital effects overlaid on an augmented physical space or mixed reality environment (Lindgren et al., 2013). Others still have players situated in a completely physical environment where their physical actions are tracked primarily to keep score or digitally maintain information related to learning content that is displayed during the interaction (Gnoli et al., 2014).

Figure 2: Three systems illustrating PDt transforms in different learning environments. Left - physical actions are mapped as input into a virtual environment (Lyons et al., 2013). Middle - physical actions are mapped as input into a mixed reality environment that is overlaid on physical space (Lindgren et al., 2013). Right - physical actions occur in a physical learning environment and are only tracked to digitally maintain and display information related to the physical interaction (Gnoli et al., 2014).

APPLYING THE DESIGN FRAMEWORK FOR EMBODIED LEARNING GAMES AND SIMULATIONS

Example 1 - Categorizing Existing Games and Simulations

One fundamental feature of any framework is its descriptive capability. To exemplify how designs of existing embodied learning games and simulations can be described using our framework, we applied it to the 48 systems identified in our earlier literature review. For each design, we assigned dimensional values and cataloged the results (see *http://edwardmelcer.net/research/supplementary_framework_table.pdf*). This methodical approach provided us with a means to systematically compare and contrast the different designs (Ens & Hincapié-ramos, 2014). One important point to note is that our framework does not perfectly partition every design into dimensional values. There were some cases where multiple values within a dimension would match a single design or the design description would leave a chosen value open to interpretation. However, we believe these minor discrepancies are acceptable since the intentions of a design framework are to make the designer aware of important design choices and help them weigh the potential benefits of these choices, rather than provide a set of arbitrary sorting bins (Ens & Hincapié-ramos, 2014).

During the analysis and cataloging process, a variety of similar designs emerged and were reasonably described by 9 distinct categories (see Figures 3 & 4). We found the majority of reviewed designs (42 of 48) to be a very good fit for one of the categories, despite all 9 categories only representing a small portion of the full design space expressed by the framework. Similar to the assignment of dimensional values, categories are not absolute. Therefore, we include designs with minor variations in a category so long as they fit closely to the overall characteristics of that group.

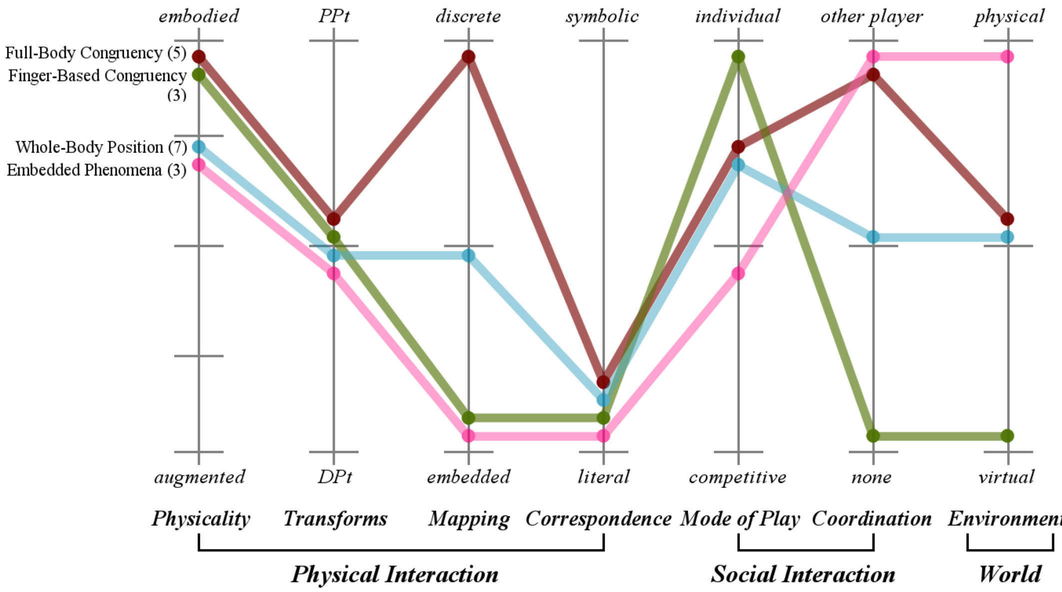

Figure 3: A parallel coordinates graph showing the categories found during analysis of existing designs that utilize *embodied* and *enacted* physicality.

Embodied Physicality Categories (Figure 3)

Full-Body Congruency describes designs that employ full-body interactions with all or a portion of the body being utilized as input into a mixed reality environment. The mapping of input to output is discrete and sensor-based (e.g., utilizing some form of IR or computer vision tracking), where players see augmented video feedback of themselves moving to match virtual objects or actions depicted on a screen. The educational focus of these systems is on mirroring a learning concept through bodily or gestural congruency, and instances include using the body to match shapes of alphabet letters (Edge et al., 2013; Paul et al., 2015; Yap, Zheng, Tay, Yen, & Do, 2015) and geometric shapes (Mickelson & Ju, 2011).

Finger-Based Congruency is conceptually similar to full-body congruency in that the educational focus of designs is on mirroring a learning concept through physical or gestural congruency. However, the interaction focus is instead on usage of fingers to achieve this congruency. This results in an embedded mapping of input to output on a physical device (e.g., tablet) where gameplay is situated in a virtual environment. Examples of this design category include usage of fingers to represent the numbers in a part-whole relation (Barendregt & Lindström, 2012) and the velocity of a moving object (Davidsson, 2014).

Enacted Physicality Categories (Figure 3)

Whole-Body Position is one of the largest set of systems categorized (7 designs) and focuses on tracking simple aspects of a player's body, such as their location in physical space, to enact learning concepts in a mixed reality environment. These systems typically focus on augmenting the physical space with a co-located mapping of input through motion tracking and output through top down projections (Kelliher et al., 2009; Lindgren et al., 2013) or through different modalities such as sound (Antle, Droumeva, & Corness, 2008).

Embedded Phenomena is a class of simulations that embed imaginary dynamic phenomena—scientific or otherwise—into the physical space of classrooms (Moher, Hussain, Halter, & Kilb, 2005). As a result of this design approach, interaction revolves around enacting techniques performed by real world professionals in order to measure and utilize devices embedded into the physical classroom environment that provide augmented feedback about a specific phenomena. Examples of this design category include simulations of earthquake trilateration (Moher et al., 2005) and subterranean water flow (Novellis & Moher, 2011).

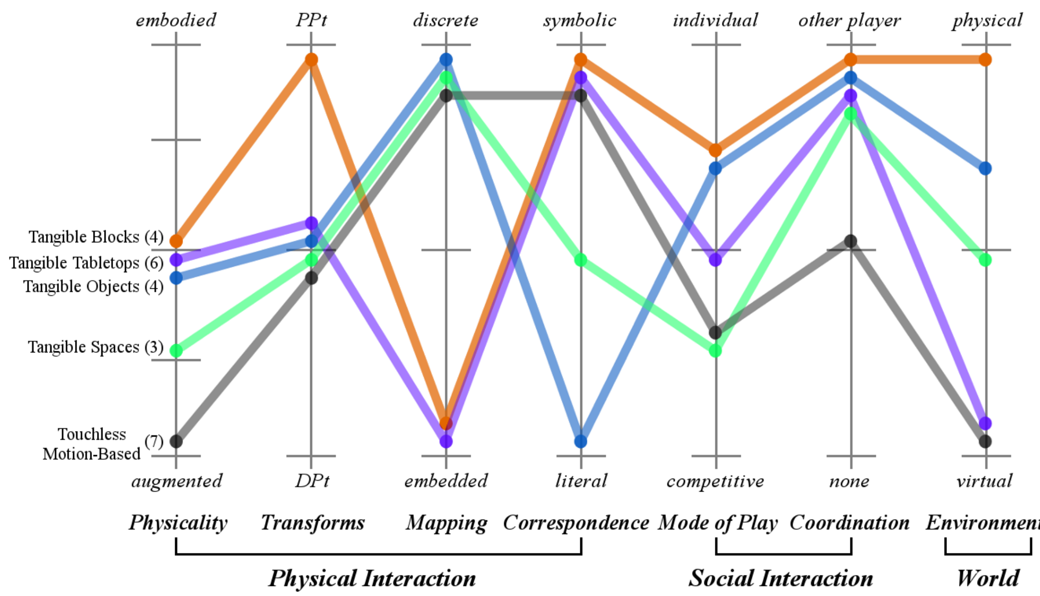

Figure 4: A parallel coordinates graph showing the categories found during analysis of existing designs that utilize *manipulated, surrogate,* and *augmented* physicality.

Manipulated Physicality Categories (Figure 4)

Tangible Blocks describe designs that utilize notions of tangibility and embodied interaction from HCI and TEI communities combined with concepts of modularity from Computer Science. Players physically manipulate/program a set of tangible blocks with embedded sensing capabilities and feedback systems. These blocks interact within the physical environment and are usually symbolically representative of physical computing concepts (Schweikardt & Gross, 2008; Wyeth & Purchase, 2002; Wyeth, 2008).

Tangible Tabletops describe designs that similarly utilize notions of tangibility and embodied interaction, but instead focus on the usage of symbolic tangibles or gestures in conjunction with a virtual world displayed on an interactive tabletop. The setups are commonly found in public spaces such as museums and typically facilitate large scale social interactions. Tangible tabletop designs have been employed to teach educational concepts around energy consumption (Esteves & Oakley, 2011), nanoscale (MoraGuiard & Pares, 2014), and African concepts for mapping history (Chu et al., 2015).

Tangible Objects describe designs that utilize tangibles and embodied interaction as input into virtual learning environments. Physical manipulation of the tangible object results in a discrete and intuitive mapping to a virtual representation of learning content. Tangible object designs have been utilized to teach a variety of concepts such as urban planning (Shelley et al., 2011) and heart anatomy (Skulmowski, Pradel, Kühnert, Brunnett, & Rey, 2016).

Surrogate Physicality Categories (Figure 4)

Tangible Spaces build upon a space-centered view of tangible embodied interaction where interactive spaces rely on combining physical space and tangible objects with digital displays (Hornecker & Buur, 2006). The design focus is on creating a tangible physical environment for the player to actively manipulate—complete with a physical surrogate avatar that the player controls—and discretely mapping physical changes in that space to a virtual world that either mirrors or augments the physical one. Tangible spaces have been used to teach programming (Fernaeus & Tholander, 2006), animal foraging behavior (Gnoli et al., 2014), and diurnal motion of the sun (Kuzuoka et al., 2014).

Augmented Physicality Categories (Figure 4)

"Touchless" Motion-Based designs employ a discrete mapping of players' physical actions as input into a virtual world. The use of a "touchless" interaction paradigm exploits sensing devices which capture, track and decipher body movements and gestures so that players do not need to wear additional aides (Bartoli, Corradi, Milano, & Valoriani, 2013). Unlike full-body congruency, the focus is not on mirroring a learning concept through the body, but instead that a player's physical actions are mapped to control a digital avatar in the virtual world. As a result, rather than seeing a video of themselves, players will see silhouettes, digital avatars, or a first-person perspective. These systems have been utilized to teach concepts around geometric shapes (Kynigos, Smyrnaiou, & Roussou, 2010), climate change (Lyons et al., 2013), and peer-directed social behaviors (Bhattacharya et al., 2015).

Example 2 - Identifying Problematic Design Spaces

One benefit of our design framework is that it allows us to systematically examine design elements of existing systems, identifying potential problematic design spaces. As an example of this usage, we examine the *Tangible Earth* system (see Figure 5) where the authors had to create and use an assessment framework to identify/understand problems the system encountered (Kuzuoka et al., 2014). *Tangible Earth* is designed to support learning of the sun's diurnal motion and earth's rotation. It consists of a doll-like avatar, a globe and rotating table to represent the earth and its rotation, an electrical light representing the sun, and a laptop running VR universe simulator. Learners would physically manipulate the rotation of the earth and position/rotation of the avatar to observe simulated changes in sun's position from the avatar's perspective.

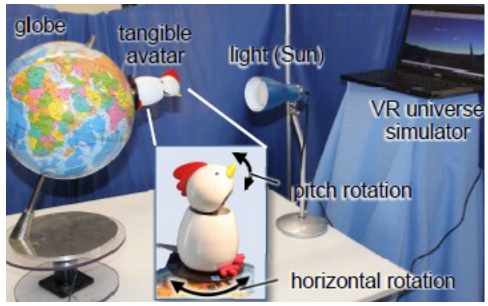

Figure 5: The *Tangible Earth* embodied learning system (Kuzuoka et al., 2014).

One of the more significant problems identified by Kuzuoka et al (2014) for *Tangible Earth* was that learners spent very little time looking at the tangibles themselves (e.g., globe, lamp, and avatar), instead focusing primarily on the VR simulation in the laptop. This proved to be especially problematic for manipulation of the avatar, where users would frequently forget the position of its body and orientation of its head. This often caused the sun to appear or disappear unexpectedly in the simulation, confusing learners and learning concepts. By analyzing this issue with our design framework, we identified a potential problematic design space (see Figure 6). Learners had difficulty remembering the position of a physical agent representative of themselves (surrogate embodiment) because all of their physical actions were mapped to digital effects (PDt) in a simulated world (virtual environment). This difficulty makes sense considering remembering the physical position/orientation of a surrogate avatar in *both* the real world and the virtual world simultaneously would introduce a significant amount of extraneous cognitive load (Plass, Moreno, & Brünken, 2010). As a result, our design framework suggests that the intersection of surrogate embodiment, PDt transforms, and virtual environments is a problematic design space that should be carefully considered when designing future embodied learning systems.

Physicality	Embodied	Enacted	Manipulated	Surrogate	Augmented
Transforms	PPt	PDt	DPt		
Mapping	Discrete	Co-located	Embedded		
Correspondence	Symbolic	Literal			
Mode of Play	Individual	Collaborative	Competitive		
Coordination	Other Player(s)	NPC(s)	None		
Environment	Physical	Mixed	Virtual		

Figure 6: Problematic design space identified by *Tangible Earth* (Kuzuoka et al., 2014).

Example 3 - Identifying Design Gaps

Another benefit of our design framework is that it allows us to methodically fill in the framework with existing systems to identify gaps and unexplored terrain (Ens & Hincapié-ramos, 2014). As an illustration of this usage, we fill in example pairings between the two dimensions of *Physicality* and *Transforms* (see Table 2). This provides examples of relevant combinations between these two dimensions in the embodied learning systems literature.

Transforms \ *Physicality*	*Embodied*	*Enacted*	*Manipulated*	*Surrogate*	*Augmented*
PPt		*Scratch Direct Embodiment* (Fadjo & Black, 2012)	*Electronic Blocks* (Wyeth, 2008); *roBlocks* (Schweikardt & Gross, 2008)		
PDt	*SpatialEase* (Edge et al., 2013); *Word Out!* (Paul et al., 2015); *Mathematical Imagery Trainer* (Howison et al., 2011)	*Embodied Poetry* (Hatton et al., 2009); *AquaRoom* (Novellis & Moher, 2011); *MEteor* (Lindgren et al., 2013)	*Mapping Place* (Chu et al., 2015); *MoSo Tangibles* (Bakker et al., 2011); *Eco Planner* (Esteves & Oakley, 2011)	*Hunger Games* (Gnoli et al., 2014); *Tangible Programming Space* (Fernaeus & Tholander, 2006); *Tangible Earth* (Kuzuoka et al., 2014)	*Human SUGOROKO* (Nakayama et al., 2014); *Bump Bash* (Bartoli et al., 2013); *Sorter Game* (Kynigos et al., 2010)
DPt					*ALERT* (Lahey, Burleson, Jensen, Freed, & Lu, 2008)

Table 2: Example pairings between the *Physicality* and *Transform* dimensions.

Examining Table 2, we find several design gaps for existing embodied learning games and simulations. Some of the more potentially useful pairings in the identified design gaps are Embodied + PPt, Manipulated + DPt, Surrogate + PPt, and Surrogate + DPt, where interesting future system designs could evolve from utilizing one of these pairings. For instance, using a Surrogate + PPt pairing could lead to the design of physically embodied educational board games. Additionally, a Surrogate + DPt pairing could lead to an asymmetric computational thinking game where one player controls and interacts with a physical avatar while another player digitally designs the physical courses and obstacles for the first player to complete.

CONCLUSION AND FUTURE WORK

In this paper, we presented our design framework for embodied learning games and simulations based on a detailed analysis of 48 existing embodied learning systems and related frameworks/taxonomies from subdomains and communities such as TEI, HCI, embodiment and embodied learning, and mixed reality. A design framework allows us to systematically understand, analyze, and differentiate design elements of existing embodied learning systems. This ultimately aids us in determining where and how embodiment occurs in an educational system, and guides the application of specific design choices in future systems. Future work will build games and simulations addressing design gaps and problematic spaces identified by our framework, and test the efficacy and learning outcomes of these systems. In broader application, this design framework can also be used to guide construction of systems that methodically examine questions of *when* and *how* embodied learning should be used within games/simulations; which will help to further ground the framework and clarify its interpretation.

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