Embodied Learning Mechanics and Their Relationship to Usability of Handheld Augmented Reality

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ABSTRACT

Researchers in HCI have designed and developed Augmented Reality for over two decades. Recently, there has been increased interest in exploring an embodied perspective on interaction, where the focus is on the fundamental role played by the physical body in how we experience. This paper presents an overview of embodied cognition as it relates to augmented reality, along with specific interaction mechanics that can engage embodied learning in augmented reality. Further, we reflect on children's usability of handheld augmented reality, presenting a set of usability problems encountered by children, and reflections on how these problems impact the use of embodied interaction learning mechanics for young children.

Keywords: Embodied Cognition, Embodiment, Children, Interaction Design, Physicality, Tangible Interfaces, Augmented Reality, Education, Teaching, Pedagogy

Index Terms: H.1.2 [Models and Principles]: User/Machine Systems – *software psychology*; H.5.2 [Information interfaces and presentation]: User Interfaces – *theory and methods*.

1 INTRODUCTION

The field of interaction design for children is built on a long-standing assumption taken from developmental psychology that a child's development, particularly in the early years, depends on and is influenced by activity in the environment. In 1963 Held & Hein expose the critical role of action in the development of vision with the twin kitten experiments [1]. Piaget also posited as early as 1952 that even very young infants use their experiences of actions to shape their perception of the world [2]. Theories of experiential learning, beginning with Dewey in 1938 [3], culminating with Kolb in 1984 and 2014 [4,5], have heavily influenced pedagogical research and practice in learning sciences and in educational technology -- not just for children but for lifelong learning. Dewey wrote that "successive portions of reflective thought grow out of one another and support one another". Through iterative cycles of *experience* and *reflection* a child participates in their own learning process through their body senses and their minds' perceptual, interpretive, analytical and reflective processes. While there are many theories that describe what is needed for experiential learning to proceed, the specific mechanisms through which direct experience supports learning have not been clearly defined. Kontra *et al*. suggest that theories of embodied cognition provide the background for which we can understand how a child's development unfolds, particularly the role action and experience in different environments have on the development of perception, empathy, thinking and reasoning [6]. For example, mirror neurons provide evidence that there is a direct link between our own brain body system and the brain body system of other individuals. Gee argues that a projected identity in video games enables embodied empathy for another human or system [7]. In addition, it prepares us for goal direction action-behaviour. Players become not just systemic thinkers but ethical actors. We are not just learning *about* system but learning how to *be within* that system.

Augmented reality (AR) is an emerging technology that enables students to be physically interacting with the learning content, and to engage in whole-body embodied learning. AR has been shown to have measurable benefits to student education on a variety of platforms that range between smartphones, tablets, webcam-enabled computers and head-mounted displays. This technological innovation has the potential to engage students in more effective kinds of learning than compared to traditional approaches, by leveraging the specific affordances of AR media: presenting educational content that is spatially- and temporally- integrated with real physical objects, engaging students with interactive 3D simulations of risky or infeasible real-life phenomena, guiding learner's attention by highlighting items in their environment, lowering cognitive load by allowing interaction through natural motions, and enabling learning through embodied cognition [8,9].

In this paper, we start by outlining five ways in which AR experiences can engage embodied learning. Following, we provide our research findings about usability of handheld augmented reality interfaces for elementary-school children, and use this data to reflect on the possibilities of children engaging with the embodied interaction mechanics.

Although this paper is specifically focused on handheld augmented reality, the embodied interaction mechanics can be applicable to other technology platforms that engage the whole body, such as virtual reality, wearables, tangible interfaces, etc.

2 EMBODIED LEARNING AND AUGMENTED REALITY

There are various ways in which the body can be engaged through augmented reality experiences. In this section, we discuss how embodied learning can be enabled at the basic level of a user interacting with a system, and we present five embodied interaction methods that can be encouraged by whole-body technologies.

2.1 Method 1: Perspective Change Through Movement

The simple act of moving the body is a rich physical experience that can have beneficial learning effects to spatial comprehension and memory encoding [10]. All augmented reality experiences are inherently spatial, whereby students can easily move around 3D simulations to experience them from different perspectives.

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However, not all experiences are designed to encourage this behaviour.

AR experiences can be played by standing still without much body movement around a space (e.g. solving 3D spatial puzzles while sitting at a desk [11]), or by standing still and simply rotating the body in place (e.g. while shooting aliens in the sky). In these experiences, the user's understanding of space is enhanced by their ability to continuously see 3D content as they perform small-scale movements with their body.

Additionally, AR experiences can be explicitly designed to require changes of perspective, either by walking around an augmented object (e.g. in order to collect items inside tunnels [12]), or by using one's hands to rotate an augmented object (e.g. in order to visualize a solar system [10]). Research on the latter system [10], showed that students who viewed a solar system simulation using head-mounted displays had higher post-test scores than compared to the group who viewed the same simulation on a PC interface. This indicates that encouraging the use of the body to move around educational simulations is beneficial for learning. Similarly, AR experiences can be designed to explicitly take advantage of physical body motions by providing viewpoint-dependent content (for example, when viewing a building architecture, the simulation could show internal structures when the user is close, or show forces and wind currents when the user is far).

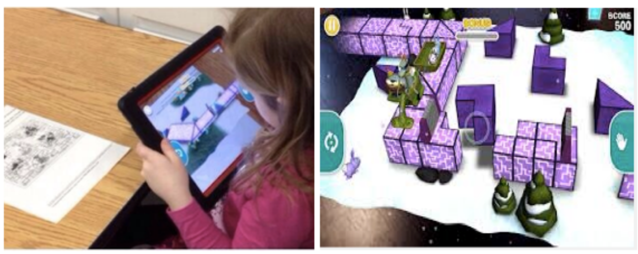

Figure 1. The spatial game Cyberchase Shape Quest [8]

2.2 Method 2: Exploration Through Physical Action

When a problem is being solved using physical components, such as when a student is solving a jigsaw puzzle or solving a math problem using physical blocks, part of the student's cognition is being offloaded into the physical world. Distributed cognition theory explores how human cognition occurs both inside the mind and outside in the physical environment. Examples include the use of sticky notes and calendars as external storage to ease our memory; and the use of visual project timelines and concept maps, as external aids for organizing and communicating information [13]. Epistemic actions are exploratory physical activities for offloading, in which a student takes physical actions to change his or her own computational state in order to make mental computation easier, faster, or more reliable [14]. For example, students solving jigsaw puzzles rotate pieces in order to transform the problem space [15], and students using blocks for math problems move the blocks to aid classification and memory [16].

In augmented reality experiences, the user is physically interacting with three-dimensional simulations, and the experience can be designed to permit (or even encourage) distributed cognition and epistemic actions. For example, in [11] (Figure 1), students solve spatial puzzles by manipulating virtual puzzle pieces which change shape as students progress through the game; the experience is designed to engage children's spatial visualization skills, by supporting playful exploration and manipulation. The ease of picking up, rotating, and dropping virtual pieces encourages exploration and problem solving in the augmented 3D space. In one of the AR mathematics applications presented in [22] (Figure 2), students can connect and disconnect augmented Lego blocks in order to explore concepts of number composition. Technology can allow such intuitive body-based exploratory manipulation to be applied to all kinds of 3D simulations. Furthermore, AR can encourage students to use space as a means of offloading cognition – for instance by attaching information to spatial locations (ex: adding text messages to locations or objects in a room); or by adding functionality to specific spatial locations (ex: dividing a desk into virtual areas for grouping similar objects), etc. In these examples, the ease of using the system is facilitating improved understanding, because it enables easy exploration and reorganization of the problem space.

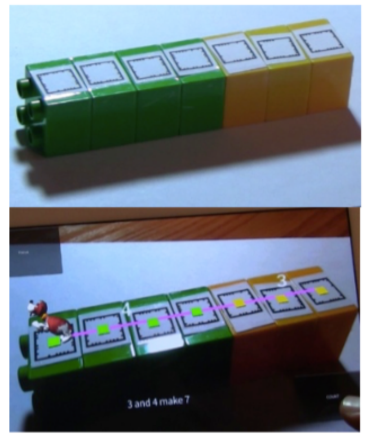

Figure 2. Physical exploration of numbers through AR [22]

2.3 Method 3: Reenactment Through Physical Action

Research shows that physically enacting educational content leads to stronger learning effects [18]. For example, children remember a story better when they are asked to physically enact the story [19]; students do better on math on math problems when they are allowed to gesture [20]. These active experiences create better learning experiences because students become more engaged with the content as they are required to gesture and correctly remember the material while re-enacting it.

Augmented reality can be designed to encourage these interactions. For example, in a tablet-based system presented in [21], children had to pick up stranded animals and drop them off at a safe house, through distance-based interactions. AR environments can encourage other kinds of gestures in relation to re-enacting 3D simulated phenomena, at the same time as the system provides feedback on the gesture. For example, using hands to act the steps in a word problem (which has been identified by teachers as being a valuable potential AR application [22]), counting objects in a room with the aid of a virtual assistant, acting the movements of an electron as it travels in a wire, etc.

2.4 Method 4: Interaction with Abstract Concepts

Digital technology allows designers to represent abstract concepts in physical form. For example, a system can represent "musical style" as a virtual box that can be stretched and squished through physical actions that cause changes in music; or, a system can represent a country's unemployment rate and economic output as two virtual balloons linked together, which can be interacted by using hand motions. In such cases, abstract information is reified into a physical form that users can physically interact with.

Designing the appropriate representations and interactions is a challenging aspect of designing such experiences, because abstract concepts do not have tangible real world representations. Research in embodied cognition can assist the design process. Embodied cognition research adheres to the philosophy that human thought is grounded in the body and its interaction with the external environment. It has been hypothesized that some patterns of thinking (cognitive schemata) are developed from, and accessed in conjunction with, gestalts of basic physical experience [15]. That is, our ways of thinking about things are rooted in the physical experience of having human bodies. This effect is visible in examples from linguistics, for example the notion that physical orientation and direction are tied to the more abstract concepts of: happiness (hence the expression of "I'm feeling down") and "time" (thus, "that even is coming up") [23]. Such "embodied" metaphors relate physical experiences to abstract concepts.

In augmented and virtual reality experiences, abstract concepts can be given a virtual form which is typically three dimensional and feels like a physical object. To interact with these representations, users will perform physical actions. It is important for designers to create physical interactions that fit with the user's embodied metaphors.

Embodied metaphors have been studied in the context of whole-body technologies. For example the research in [24,25] shows that children thought of sounds as being related to smooth or jagged movements. In AR authoring environments, activities have been designed to observe and elicit children's existing embodied metaphors [26]. Such embodied metaphorical mappings can also be taught. For example in a non-AR setting, [27] when students engaged with a tangible application to make gestural movements related to proportions and received feedback, their understanding of proportions improved. Further research is necessary for creating interactions that match user metaphorical thinking with abstract concepts.

2.5 Method 5: Embodying New Entities

Technologies on the mixed reality spectrum, can be used to immerse a user in the living experiences of other entities. In [28] we proposed a VR body suit capable of connecting the user's experience to a robotic ant which lives inside a natural ecosystem with other ants, or to a bacteria which travels through the respiratory system of a larger organism. Although this technology is in the future, it does have potential to stimulate students in experiencing new perspectives. In a current day system, [29], the authors study children's learning of astronomy in the context of an interactive projector-based environment, where children move along the trajectory of asteroids. In a controlled test of learning effects, the authors find that children in the AR condition, who used this system by moving their bodies, showed deeper learning than compared to children using a similar PC-based simulation.

Immersive whole-body technologies can allow users to embody other entities; but it is unclear how strongly the effect is when users can see the human body and the familiar perspective which they experience on a daily basis. Further research is required to understand under what immersion and interaction conditions students experience learning through embodying new entities.

3 Usability in Handheld Augmented Reality

In order for children to benefit from embodied learning through the methods outlined above, first children need to be capable of engaging with the technology itself. Children's undergo significant physical and cognitive development in the early years of life, and with changes in development come changes in ability to use technology. In our studies we have investigated the usability of handheld augmented reality for elementary-school children, and we find that children of different ages can experience problems that limit their ability to engage with embodied learning experiences.

A large set of usability problems in augmented reality has been presented in [31], and comparisons of children aged 5-10 years old playing handheld augmented reality games are presented in [12]. The data in the latter studies was analyzed through qualitative and quantitative methods. Quantitative metrics were collected for player performance, subjective experience, developmental skill, etc. For qualitative analysis, a coding scheme was developed for detecting usability problems from video observations, which generated the set of usability problems visible in Table 1. For more information and guidelines please see [31].

Observed Behaviours	Stationary levels num. children 5-6 / 7-8 / 9-10 y.	Walking levels num. children 5-6 / 7-8 / 9-10 y.
MANIPULATION		
Strained body posture	0% / 14% / 33%	0% / 28% / 33%
Strained grip	0% / 21% / 0%	0% / 21% / 16%
Dropping the phone	0% / 7% / 8%	7% / 0% / 8%
SPACE		
Difficulty orienting body in relation to the gameboard, while playing the game	0% / 0% / 0%	21% / 50% / 0% **(7% / 0% / 0%)**
Difficulty orienting body in relation to the gameboard, while fixing tracking	0% / 0% / 0%	50% / 7% / 0% **(42% / 7% / 0%)**
ABSTRACT THINKING		
Needing tutorial instruction on how to use crosshair	71% / 79% / 58% **(71% / 79% / 58%)**	NA
Needing in-game instruction on how to use crosshair	7% / 7% / 0% **(7% / 7% / 0%)**	7% / 0% / 0% **(7% / 0% / 0%)**
Not understanding storyline	0% / 14% / 0%	7% / 7% / 8%
Not understanding mechanics	7% / 0% / 0%	14% / 14% / 0%
Difficulties interpreting or fixing tracking loss	14% / 7% / 0% **(7% / 0% / 0%)**	50% / 14% / 16% **(42% / 14% / 0%)**
ATTENTION		
Bumping or tripping	7% / 0% / 0%	28% / 35% / 41%
Interruption due to self-distraction	0% / 0% / 0%	21% / 7% / 0%
Interruption due to scratching	0% / 35% / 50%	21% / 35% / 58%

Table 1. Total number of distinct children in each age group, encountering problematic behaviors in levels with open targets vs. levels with tunnel-enclosed targets. Bold text indicates how many children encountering issues requiring assistance from experimenter.

Overall, children of different ages encounter different usability problems with handheld AR. The number of severe usability problems decreased as children's age increased. Younger children experienced higher frequency and higher severity of problems, especially when required to change perspective around a gameboard. Children 5-6 years old had significantly weaker performance than compared to both 7-8 and 9-10 year old groups on several metrics, indicating a possible developmental gap around age 7. A large set of problems were observed related to children being unable to recover from tracking loss (while using Vuforia image-based tracking). Physical manipulation was also a problem, as younger children were unable to perform independent movements with both hands (such as using a paddle while holding the phone). Children used a variety of grips and trends were detected with increased age, suggesting that crosshair-based interaction is easier for younger children than finger-based tapping (Figure 5). Older children generally performed better, but encountered other problems. Older children showed more posture strains due to their increased height (Figure 3). Technology exposure was correlated to increased number of tracking losses due to fingers in front of the camera, and lessened accuracy, indicating that children with more technology experience will need to be un-trained when using novel technologies such as handheld AR.

Figure 3. Examples of strained body posture.

4 Handheld AR Embodied Design Implications

The fact that children cannot perform specific actions with handheld augmented reality is a factor that limits their ability to engage with embodied interaction mechanics outlined above.

Changing perspective while holding a mobile device and looking at an augmented space is a task that be achieved by most elementary-school children [12]. However, when the AR experiences require changes in perspective, young children encounter tracking losses and inability to orient their bodies appropriately, and this can be a problem if the experience requires frequent or fast changes in perspective. Additionally, young children typically held the phone with both hands, and were unable to perform actions which required moving physical objects while holding a phone. Also, attentional issues were encountered, and it is unclear at what age children understand the experience on a mobile phone screen to be associated with a physical space. Therefore it is likely that even young children can make use of embodied learning through whole-body motion, but experiences need to be designed to be simple enough in terms of physical manipulation and space movement.

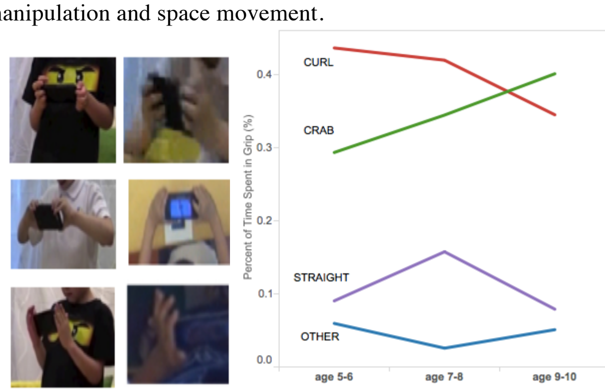

Figure 5. Grips used by children: Curl (left top), Crab (left middle), Straight (left bottom). And percentage of time each grip was used by children of different ages (right).

Exploration through physical action, as well as reenactment through physical actions, can be achieved if the interface allows users to perform actions easily, and if users can undo errors easily. Such fluid interaction encourages exploration and reenactment through physical manipulation. For manipulating on smartphones, young children will have trouble using external tools such as paddles, but they are capable of manipulating items by touching on screens and using crosshairs. It is suggested to manipulate items through selection rather than drag-and-drop, as is unclear at what age children can drag with the finger on the screen while holding up a phone to look at a marker. For larger devices such as tablets, children will likely be unable to hold them while touching the screen, therefore crosshair-based interactions are suggested. Crosshairs are sufficient for exploratory actions, but for reenactment they may be weak triggers of embodied learning since crosshair interaction engages the body to a lesser degree than pointing activities. Exploratory and reenactment activities can benefit from movement around a space; however be wary of children bumping into physical objects in their environment, as they focus on the virtual content.

Interaction with abstract concepts is possible to achieve with young children in HAR, depending on the type of interaction that is designed. As mentioned above, children will not be able to perform complicated gestures while holding a mobile screen; however, it is possible to use large body motions as metaphorical interactions. For example, children can interact with virtual items by moving close/far, by crouching or stretching, etc. This encourages large body motions which can relate to embodied metaphorical thinking. However, note that young children were observed to encounter frequent tracking losses and inabilities to recover from tracking losses, especially when performing large movements around a gameboard; these issues may be reduced with advances in tracking technologies.

The last embodiment mechanic of embodying new entities is perhaps the most difficult to achieve and most complex to analyze in terms of children's usability. This is because there are multiple methods for simulating that a user is embodying different entities. No research exists of children embodying entities through mobile devices, likely because small mobile device screens offer limited possibilities of immersion. Projection-based systems and head-mounted systems offer improved possibilities for immersion, and various handheld devices can improve the ability to physically feel and interact while embodying other entities. Further research is needed to understand the usability limitations of these kinds of experiences for young children, and multiple factors will need to be researched - ranging from ergonomic and content design, to children's conceptual understanding of the reality of immersion.

References

[1] Held, R. and Hein, A., 1963. Movement-produced stimulation in the development of visually guided behaviour. Journal of comparative and physiological psychology, 56(5), 872.

[2] Piaget, J., 1952. The origins of intelligence in children. New York: International Universities Press.

[3] Dewey, J., 1938. Education and experience.

[4] Kolb, D., 1984. Experiential learning as the science of learning and development. Englewood Cliffs, NJ Prentice Hall. 1984.

[5] Kolb, D.A., 2014. Experiential learning: Experience as the source of learning and development. FT press.

[6] Kontra, C., Goldin-Meadow, S. and Beilock, S.L., 2012. Embodied learning across the life span. Topics in cognitive science, 4(4), 731-739.
[7] Gee, J.P., 2003. What video games have to teach us about learning and literacy. Computers in Entertainment (CIE), 1(1), 20-20.
[8] Radu, I. (2014). Augmented reality in education: a meta-review and cross-media analysis. Personal and Ubiquitous Computing, 18(6), 1533-1543.
[9] Bujak, K. R., Radu, I., Catrambone, R., Macintyre, B., Zheng, R., & Golubski, G. (2013). A psychological perspective on augmented reality in the mathematics classroom. Computers & Education, 68, 536-544.
[10] Shelton, B., & Hedley, N. (2004). Exploring a cognitive basis for learning spatial relationships with augmented reality. Technology, Instruction, Cognition and Learning, 1(4), 323–357.
[11] Radu, I., Doherty, E., DiQuollo, K., McCarthy, B., & Tiu, M. (2015, June). Cyberchase shape quest: pushing geometry education boundaries with augmented reality. In Proceedings of the 14th International Conference on Interaction Design and Children (pp. 430-433). ACM.
[12] Radu, I., MacIntyre, B. and Lourenco, S., 2016, June. Comparing Children's Crosshair and Finger Interactions in Handheld Augmented Reality: Relationships Between Usability and Child Development. In *Proceedings of the The 15th International Conference on Interaction Design and Children* (pp. 288-298). ACM.
[13] Hollan, J., Hutchins, E. and Kirsh, D., 2000. Distributed cognition: toward a new foundation for human-computer interaction research. *ACM Transactions on Computer-Human Interaction (TOCHI)*, *7*(2), pp.174-196.
[14] Kirsh, D. and Maglio, P. (1994) On Distinguishing Epistemic from Pragmatic Actions. Cognitive Science, 18, 4, 513–549.
[15] Antle, A.N. and Wang, S. Comparing motor-cognitive strategies for spatial problem solving with tangible and multi- touch interfaces. In Proceedings of Conference on Tangible, Embedded and Embodied Interaction (TEI ’13), ACM Press (Barcelona, Spain, February 10-13, 2013), 65-72.
[16] Manches, A., O’Malley, C., & Benford, S. (2010). The role of physical representations in solving number problems: A
[17] comparison of young children’s use of physical and virtual materials. Computers & Education, 54(3), 622-640.
[18] Goldin-Meadow, S., 2005. Hearing gesture: how our hands help us think. Cambridge, MA, USA: First Harvard University Press.
[19] Glenberg AM, Brown M, Levin JR (2007) Enhancing comprehension in small reading groups using a manipulation strategy. Contemp Educ Psychol 32:389–399
[20] Goldin-Meadow S, Cook SW, Mitchell ZA (2009) Gesturing gives children new ideas about math. Psychol Sci 20(3):267– 272
[21] Radu, I. and K. Bujak. (2012). "Argon Games: Mountain Rescue and Bacteria Snap." Retrieved August 3, 2013, from http://argon.gatech.edu/games/.
[22] Radu, I., et. al. (2016). Discovering Educational Augmented Reality Math Applications by Prototyping with Elementary-School Teachers. Virtual Reality (VR), 2016, IEEE.
[23] Lakoff, G., & Johnson, M., 1980. Metaphors we live by. Chicago, IL: University of Chicago Press.
[24] Bakker, S., Antle, A.N. and van den Hoven, E. Embodied metaphors in interaction design, Personal and Ubiquitous Computing, Special Issue on Children and Tangibles, (2012), 433-449.
[25] Antle, A.N., Corness, G. and Droumeva, M. What the body knows: Exploring the benefits of embodied metaphors in hybrid physical digital environments, Interacting with Computers, 21, 1-2 (2009), 66-75.
[26] Radu, I., Xu, Y., & MacIntyre, B. (2013, June). Embodied metaphor elicitation through augmented-reality game design. In Proceedings of the 12th International Conference on Interaction Design and Children (pp. 412-414). ACM.
[27] Abrahamson, D., & Trninic, D. (2011). Toward an embodied-interaction design framework for mathematical concepts. Proceedings of the 10th annual interaction design and children conference (pp. 1–10).
[28] Radu, I. and Antle, A.N., 2016, June. All Creatures Great and Small: Becoming Other Organisms through the EmbodySuit. In *Proceedings of the The 15th International Conference on Interaction Design and Children* (pp. 751-758). ACM.
[29] Lindgren, Robb, and J. Michael Moshell. "Supporting children's learning with body-based metaphors in a mixed reality environment." Proceedings of the 10th International Conference on Interaction Design and Children. ACM, 2011.
[30] Radu, I. and B. MacIntyre (2012). Using children's developmental psychology to guide augmented-reality design and usability. Mixed and Augmented Reality (ISMAR), 2012 IEEE International Symposium on, IEEE.
[31] Radu, I. (2016). Exploring the Usability of Augmented Reality Interaction Techniques During Children's Early Elementary-School Years (Doctoral dissertation, Georgia Institute of Technology).