International Society of the Learning Sciences

Embodied and Non-Embodied Technologies in Mathematics Learning: A Comparative Study

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Abstract: WearableLearning is a multiplayer, game-based digital learning environment in which students use mobile devices and collaborate while physically engaging with mathematical concepts such as geometry. This study examines how students learn mathematics in embodied games enabled by WearableLearning compared with a traditional seated digital learning environment. We report results from a randomized controlled trial conducted in a U.S. afterschool program, showing that students with lower prior knowledge benefited the most from the technology-supported embodied learning condition.

Introduction and background

Much research has highlighted embodied learning as a powerful pedagogical approach for introducing and developing mathematical thinking skills (Nathan, 2021; Flood, Shvarts & Abrahamson, 2020). At the heart of embodied learning, the notion of embodied cognition asserts that knowledge is built from a continuum between the mind, body, and the physical world around us, suggesting that incorporating sensorimotor processes in lessons will strengthen learning through the learners' use of their bodies, reflection, and social interaction (Ma, 2017; Georgiou & Ioannou, 2019). Embodied cognition posits that learning involves new ways of moving and interacting with the world around us and the artifacts within our environment, involving figuring out how to move differently, following from a new way of perceiving the environment, using artifacts that can improve our "perception for action" and extend our perception–action loops (Abrahamson et al., 2024). By using these artifacts, we adopt their inherent mechanisms of disciplinary practices, consisting of gestures, discourse, and actions. Here, knowing, as woven in with doing, manifests itself as physical actions that extend the notion that these actions are thinking made visible (Nemirovsky et al., 2012).

Learning Technologies for mathematics widely used in schools, such as Intelligent Tutoring Systems (ITS), have traditionally been screen-based, with students sitting down in front of a computer in isolation from each other, and do not encourage learners to engage in embodied learning practices and typically uses chat windows for collaboration (Rasul et al., 2023a; Jeong & Hmelo-Silver, 2016). Given greater evidence supporting the importance of incorporating embodiment into pedagogy, there is also a need for new learning technologies and for developing ways to support learners through embodiment (Abrahamson et al., 2020; Abrahamson et al., 2024; Hostetter & Alibali, 2008).

With this in mind, the Advanced Learning Technologies Lab, with support from the NSF, has developed a novel learning technology called **WearableLearning (WL)** that promotes K–12 mathematics thinking and learning through physically active (both tangible and embodied) multiplayer math games on mobile devices. Prior research demonstrates improved performance on math tests after engaging with embodied physically active math games using the WL platform (Arroyo et al., 2020; Arroyo et al., 2021; Rasul et al., 2023a; Crabtree et al., 2024). However, there is a lack of controlled studies where the main difference between conditions is the embodiment within activities. This paper compares two learning conditions to answer the question: *To what extent do students learn mathematics differently through tangible and embodied activities facilitated by WearableLearning compared to traditional learning technology that teaches the same mathematical concepts?*

The Common Core State Standards for Mathematics (CCSSM) and Mathematical Practice (SMP) emphasize conceptual understanding, real-world application, and collaborative problem solving. They highlight how math knowledge develops through social interaction, shared reasoning, and engagement with meaningful models. Sensory-motor actions, gestures, and interactions play a key role in learning, as cognition is distributed across the mind, body, and social context (Goldin-Meadow et al., 2009; Congdon et al., 2017). Students also learn by manipulating tangible objects and engaging face-to-face with peers and teachers (Abrahamson, 2024).

Yet, most learning technologies are static (Cook et al., 2016), and do not employ embodied learning, which moves the interactions, at least partly, "off the screen", engaging in hands-on socially rich activities Embodied design principles are a lens for examining how digital resources are created and brought to life in mathematics learning tasks. For instance, Klemmer et al. (2006) reiterate that themes of embodied interaction design are central to understanding how the physical and social contexts of human action influence human-computer interaction. These essential guiding themes are: a. Thinking Through Doing: embodied interaction

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highlights physical engagement in creative and problem-solving processes, b. Performance: incorporating an artifact such that you act through it rather than on it, c. Visibility: Making users' actions and intentions visible to others fosters better collaboration and coordination, d. Risk: Physical action carries a certain risk in terms of possible harm, which follows from making a choice that may not be simple to undo, e. Thick Practice: action is situated in specific social, physical, and cultural contexts. Yet, Melcer and Isbister (2016) realized that embodied games and simulations have utilized a large breadth of design approaches that often have resulted in the creation of seemingly unrelated systems. Their design framework aggregates different design approaches: 1) physical interaction, classified as: embodied, enacted, manipulated, surrogate, or augmented; 2) social interactions that the activity requires (e.g., collaborative); and 3) the role of the environment (e.g., physical/virtual/mixed world).

WearableLearning

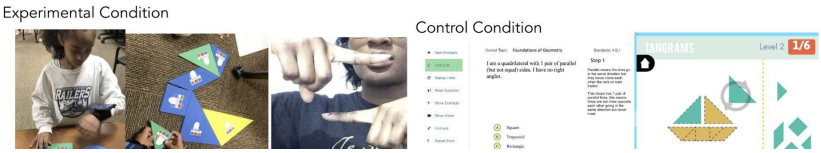
WearableLearning (WL) is a web-based platform accessed via mobile devices (e.g., smartphones or tablets) that enables the incorporation of embodied gameplay into classrooms, curricula, and standards for K-12 students (Arroyo et al., 2017; Micciolo et al., 2018). Through WL (wearablelearning.org), students engage in active, collaborative, gamified math activities, exploring physical environments, manipulating tools, interacting with peers and teachers, and internalizing learning through embodiment. Lightweight, portable devices act as "virtual assistants," guiding students and providing feedback as they navigate physical spaces and objects. Targeting the NCC, math game playing and creation with WL has been implemented with roughly 500 K–12 students, in classrooms, summer programs, and afterschool programs, as well as with 25 math teachers, who also have created a variety of games for students (Rasul et al., 2023a; Rasul et al., 2023b; Smith et al., 2020). Test scores showed improvement in math problem-solving across different areas of math and grade levels, despite short 30–40 minute exposures (Rasul et al., 2023a; Arroyo et al., 2021; Crabtree et al., 2024). All games led to learning gains, and students showed high engagement while playing, leading to implications for extending embodied learning through AI support (Rasul et al., 2023b; Arroyo et al., 2024).

WearableLearning: Tangrams race

The Tangrams Race game consists of a relay race that embraces the tangible "manipulated" form of embodied interaction (Melcer & Isbister, 2016), which regards embodied and tangible interactions using mathematically meaningful manipulatives as students learn mathematics, using hand-based manipulations, where physical objects highlight mathematical properties. A tangram is a traditional Chinese puzzle consisting of seven flat geometric pieces that can be arranged without overlap to form various shapes, recreating specific designs. The Tangrams Race requires each team to run from a start line to an end line with a basket full of geometric shapes, a subset of which are the Tangrams shapes. The mobile device (worn on the arm) provides each student various mathematical descriptions of geometric objects that they are asked to retrieve, so they can collaborate to create a Tangram arrangement at the starting line. When students find the correct shape, at the end line, they tell the phone they have found it by inputting an identifying color code (e.g. "red, green, black"), which is on each shape, into the WearableLearning (WL) app. WL provides them with immediate feedback (correct, incorrect, hints when requested), until the students collect the correct piece. Figure 1 shows how the teacher, standing at the end line, gestures with hands when students might get stuck to help students find the correct shape. Students run 3 times in each level to retrieve a geometric shape. Once all the pieces have been collected, the App tells them to work together to rearrange the pieces to replicate the desired pattern (e.g. a boat, a house, a cat) . This game has two levels, with the second being more challenging.

Figure 1

The Experimental Condition (left) vs. the Control Condition (right)



From a cognitive perspective, the Tangrams Race involves a variety of cognitive processes. At the starting line, students are provided a mathematical description of a shape, which encourages visual imagery. After running and arriving at the end line, students search through a basket full of shapes, picking up pieces to consider, physically rotating them, sensing their salient attributes such as vertices and edges, and going through a process of discerning and discarding. If students enter the code for an incorrect shape, this generates cognitive conflict that can be solved in several ways: a) students might give a try to another candidate piece; b) students can ask for

"hints" by pushing a special "hint" button; c) students may receive support from a teacher stationed at the end line, who interacts with them by asking what piece they are searching for, and who uses hand gestures to illustrate relevant properties, guiding them toward the correct geometric shape without directly revealing the answer. When all nine shapes are retrieved (three per player, and two extra pieces are simply extra distractors), the team works together to compose the 7-piece Tangram shown on their device. Note that *running* to the end line adds excitement and student engagement to the game but is not considered part of the embodied cognitive activities.

Methodology

Procedure and participants

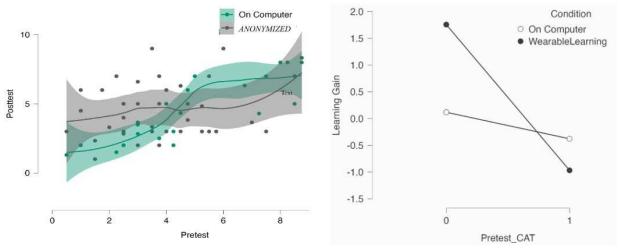
We ran a controlled study in which participants were randomly assigned to the WL (n = 37) and On-Computer (n = 26) groups (see Figure 1). The study participants were 63 students in Grades 4 and 5 enrolled in an afterschool program in the United States. These students belonged to low-socioeconomic backgrounds and historically minority communities, with regional demographics being 48% Hispanic, 29% White, and 18% Black. Students participated in the experience after their school day, typically starting around 4 pm. The Experimental Condition (left of Fig. 1) played the Tangrams Race in WL. Students used phones on their wrists to play, and retrieved geometric pieces to build the Tangram, which were color-coded. Game facilitators naturally gestured at the end line, showing parallel lines, right angles, perpendicular lines, etc. The Control Condition (on the right in Fig. 1) used a digital learning technology that delivered the same math problems and hints as the Tangrams Race. Towards the end of the session, they engaged with a Virtual Tangram, where students rotated and placed geometric pieces with the mouse. Exposure time was about 45 minutes. All participants took a pre- and post-test. The students were tested on 10 content-related questions from a 4th-grade geometry standardized exam in the United States (MCAS) on day one of their participation in the after-school program, following which they played the game and were tested again afterward. The questions chosen reflected the concepts that the game required the students to solve, thereby indicating the conceptual starting point of each student and their subsequent improvement or lack thereof. Using two tests, A and B, the pre-post test distribution was counterbalanced: half of the students received test A for their pretest, and the other half received test B; then, group A's pretest was group B's posttest, and vice versa. Counterbalancing ensured that if one test was unintentionally more difficult than the other, the difference would cancel out, preventing bias in our measure of learning. Data collection for this research began as a graduate thesis (Agbaji, 2019) and continued over multiple years, adding data incrementally to reach the required participants and achieve statistical power.

Results

There was a mean difference of +.39 and a standard deviation of 2.12 from pre-test to post-test across both conditions, indicating that students improved overall from pre-test to post-test, with the experimental group improving more. Yet, there was not a significant main effect for condition (F = 1.17, $p = 0.28$) even though the effect size was $d = 0.38$ in favor of the experimental condition (see Figure 3, Table 1). Overall, *TangramRace* students had a mean learning gain of 0.75 points (Pretest mean = 3.8, Post-test mean = 4.6), while On-Computer students showed a slight learning loss, averaging -0.16 points (Pretest mean = 4.73, Post-test mean = 4.57).

Figure 2

Left: Score (Pretest to Posttest) Right: Scores by Pretest Score and Condition, and their Learning Gai



Notably, when considering student achievement level (pretest scores indicating math ability prior to the intervention) as a factor, we found a *significant interaction effect* for Condition x Pretest Math Ability (F = 5.32, $p < 0.025$), suggesting that it was lower math ability students who benefited significantly more from the *embodied TangramsRace* condition (see Figure 2). Bonferroni contrasts confirmed that the significant interaction effect was driven by low-math-ability students performing better in the *TangramsRace* than their peers in the control

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condition (see Figure 2), indicating that the embodied TangramsRace condition was more beneficial for students with lower math ability. High-achieving students did not improve in either condition.

Table 1
ANOVA Test Results

	Sum of Squares	df	Mean Square	F	p
Playing Condition	3.9	1	3.9	1.177	0.282
Pretest Score	37.6	1	37.6	11.096	0.001
Condition x Pretest Math Ability	18.0	1	18.0	5.319	0.025
Residuals	200.0	59	3.3		

Discussion

We believe that, in general, the means are deflated due to student fatigue at the end of the school day (posttests were administered around 5 pm). Despite this, students performed better on the post-test than on the pre-test when exposed to *TangramsRace*, yet there was not a significant difference (main effect) between the experimental and control conditions. However, we found a significant interaction effect that indicated students of lower prior knowledge learned most with the embodied WL *TangramsRace* condition than the control condition ($p < 0.025$). Students in the control group were confined to their seats, limited by the stationary setup. Although they solved more problems overall and interacted frequently with the virtual Tangrams manipulative, their learning gains were smaller compared to those in the embodied condition. One explanation is that lower-achieving students have a greater need to build conceptual understanding of geometric shapes, and that the embodied condition supported this through its tangible, sensory-motor nature, which made the relevant mathematical properties more salient. This finding is important as it underscores the potential of embodied technologies to support struggling students.

Tech-supported mobilization supports teacher/peer interactions and provides instant feedback. Rich interactions beyond the digital interface expand opportunities for mathematical thinking through embodied means. This aligns with Abrahamson et al.'s (2024) ecological dynamics framework, which emphasizes grounding new concepts in the perceived affordances of physical mathematical objects and movement.

A second key difference lies in the type and extent of support that students receive from traditional learning technologies compared to WearableLearning. As stated previously, the affordances of traditional learning technologies are well known, and include immediate feedback, hints/supports, assessment data for teachers, and personal pacing through the material. While both traditional learning technologies and WL incorporate these features, closer examination reveals a distinct difference in how students experience support. Given that WL expands the range of interactions students engage in, support extends beyond the digital learning environment and teacher scaffolding. Students benefit from multi-pronged assistance: teacher support, peer support, and some collaborative interactions within their teams. Furthermore, students learning math with WL also have the advantages of tangible support—externally through hands-on interaction with physical materials, and internally through gestures and bodily engagement that help them make sense of mathematical concepts. We claim that these differences between traditional learning technologies and WL account for the differences in quantitative gains in learning, but also in qualitative observations on how students are seen learning math. Yet, further investigation is required to determine *how* these differences in the received support impact student learning.

Conclusion

Our goal was to explore how much students learn with WL as compared to traditional static learning technology. The findings from implementing WL into an afterschool program for math, in two groups–a control condition in a traditional on-computer setting and a physically/socially active condition, demonstrate that embodied learning, using action and gesture, can yield higher gains, particularly for those with lower prior knowledge.

A primary limitation of this study was that it took place in an after-school program at the end of the day, when students were either tired or being picked up by their parents during the lesson, which added noise to the data. Also, the participants were young students (3rd–5th graders). Yet, these results show that: a) it is possible to create equivalent digital math game-like conditions (digital embodied or digital sit-down); b) math ability might be a mediating factor influencing the effectiveness of embodied math tasks. New questions arise for future research: a) Does this same effect extend to other mathematics topics? b) Since the embodiment was related to hand-based manipulations of mathematical objects, does this effect extend to full-scale body embodiment (e.g., walking number lines or being fully immersed in coordinate planes, embodying points on a plane, or enacting transformations)? d) How can we assess mathematics performance in a way that is not 'sitting down' to take a test, but also to assess in an embodied manner? These are questions we intend to explore in future research.

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