

Multimodal Interactions with Virtual Manipulatives: Supporting Young Children's Math Learning

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Abstract: This study investigates how multimodal interactions impact learning in digital learning environments. More specifically, the study argues that modern virtual manipulatives should offer a rich sensory experience by presenting information visually, aurally, and kinesthetically and that carefully designed perceptual experiences will facilitate learning in young children. To test this hypothesis, sixty ($N = 60$) second grade students were randomly assigned to learn multiplication using software designed to vary the aural and kinesthetic experience while holding the visual presentation constant. The results reveal that both aural and kinesthetic interactions increased learning outcomes but in different ways and at different points. The paper concludes with a full discussion of the results as well as their theoretical and practical implications.

Introduction

In mathematics, manipulatives are objects used to introduce children to concepts that are difficult to “see” due to their abstract nature and young learners’ developmental capacity. Both physical manipulatives, such as beans and blocks, and virtual manipulatives, digital instantiations of such objects, have been shown to help children learn abstract concepts. However, weaknesses in both types of manipulatives have been identified. For example, children often struggle to connect their physical actions with manipulatives to the underlying mathematical concepts. On the other hand, virtual manipulatives designed to help children make such connections, strip-away the benefits of interacting physically with real-world objects. Given this scenario, the following study attempts to improve manipulative learning experiences by combining recent advances in input technologies with well-established multimedia learning principles.

Theoretical Framework

Manipulatives are defined as physical objects specifically designed to foster learning (Zuckerman, Arida, & Resnick, 2005) and studies have shown they can help young children learn abstract math concepts (Sowell, 1989; Suydam & Higgins, 1977; Tooke, Hyatt, Leigh, Snyder, & Borda, 1992). Other studies argue that manipulatives fail to improve student understanding (Rust, 1999; Suydam & Higgins, 1977). For example, Hiebert and Wearne (1992) observed that students performed all the physical steps correctly without understanding the target concept of place value. In another study, Thompson and Thompson (1990) described a similar situation where students failed to link their actions with manipulatives to the underlying mathematical content.

With the advent of technology, physical manipulatives have transformed into virtual manipulatives--interactive visual representations of dynamic objects that present opportunities for constructing mathematical knowledge (Moyer, Bolyard, & Spikell, 2002). Research with virtual manipulatives has found them to be promising educational tools with many advantageous properties (Suh, Moyer, & Heo, 2005). One advantageous property is their ability to help make explicit, through careful design, the connection between the virtual manipulables themselves and the abstract symbols they represent. Yet despite this benefit, virtual manipulatives suffer from a major drawback compared to physical manipulatives: the lack of developmentally appropriate physicality.

Theoretically, virtual manipulatives that takeaway the physicality of real-world manipulatives should result in a more limited sensory experience, which may, in turn, reduce learning potential. However, with today's technological advancements, it may be possible to design a virtual manipulative that offers a sensory experience similar to traditional physical manipulatives while preserving the pedagogical advantages of digital learning environments. The current study explores this idea by examining how a multi-modal virtual manipulative that can be experienced visually, aurally, and kinesthetically, impacts young children's understanding of multiplication.

Method

Research Design and Participants

To investigate the impact of a multimodal virtual manipulative on student learning, the researchers developed a computer-based virtual manipulative designed to introduce the concept of multiplication to children through

repetitive addition (details below). Using this research software, a 2×2 factorial experiment with two independent variables was designed, resulting in four experimental groups. The two independent variables were audio narration (present vs. not present) and input device (touchscreen vs. computer mouse). Students in all four experimental groups received visual information that contained mathematical notation relevant to their interactions with the on-screen graphical manipulatives. In addition to the visual math notation, some students received audio narration (A) corresponding to the visual math notation, and others received no audio narration (NA). Moreover, some students controlled the virtual manipulatives using their finger on a touchscreen device (T), while other students used a computer mouse (M). Table 1 shows the four experimental groups. Sixty ($N = 60$, Female = 22, Male = 38) second grade students from New York City public schools were randomly assigned to four groups.

Table 1: 2×2 Factorial Experimental Groups and 2×1 Control Groups

Experimental Groups		Input Device	
		Fingers on Touchscreen (T)	Computer Mouse (M)
Audio Narr.	Presence (Auditory)	A-T ($N = 15$)	A-M ($N = 14$)
	Absence (No Auditory)	NA-T ($N = 15$)	NA-M ($N = 16$)

Prior to using the software for the first time, all students took a pre-test to measure their prior knowledge and understanding of multiplication. Students with a score of more than fifty-percent were deemed too proficient in multiplication and were subsequently dropped from study. There were no significant differences between groups as measured by mean pre-test score.

After the pre-test, students used the virtual manipulative software for five sessions and took a paper-based mid-test. Students then used the virtual manipulative for five more sessions and took a paper-based post-test. The tests consisted of 33 fill-in-the-blank and matching questions, with a maximum score of 34. The format of the pre-, mid-, and post-tests was identical, however, the 33 items, and the order in which they were presented varied slightly from version to version. In total, the virtual manipulative software was used for ten sessions over six weeks. Each session lasted an average of twenty minutes and each participant completed a pre-test, mid-test, and post-test.

Research Instrument

The virtual manipulative software built for this study is called *Puzzle Blocks*. The goal of *Puzzle Blocks* is to build common shapes such as a house or a car by moving small groups of blocks repeatedly to form bigger groups of blocks. For example, if students need a group of six blocks, they build it by adding a group of two blocks three times ($2+2+2=6$). While moving the on-screen blocks, students receive visual feedback that is both graphical (the blocks) and textual (mathematical notation). In addition to visual feedback, the software provides auditory narration temporally aligned with the visual mathematical notation. For example, when students grab a group of two, they see the visual notation of “2” and hear an audio voiceover say, “two.” Similarly, when students move the group of two blocks, visual notation of “x1,” “x2,” and “x3” appears, and the corresponding audio narration reads aloud, “times one,” “times two”, and “times three”, as the blocks are dropped into place. When a larger group of blocks is complete, the full mathematical equation (i.e., “ $2 \times 3 = 6$ ”) appears and the audio voiceover reads, “two times three equals six.” The goal of this design is to help students make the connection between the graphical blocks, their actions with them, and the underlying mathematical concepts of grouping, repetitive addition, and multiplication. Importantly, the presence of the audio narration can be turned on or off by the researchers in order to form the audio narration group (A) and the non-audio narration group (NA).



Figure 1. Moving a group of two blocks three times, completes the group and the full equation is displayed

Puzzle Blocks is also designed to vary the kinesthetic interaction experienced while manipulating the on-screen blocks. This was accomplished by deploying the software on laptops and tablets. On the laptop platform, students used a traditional computer mouse (M) to manipulate the on-screen blocks. On the tablet platform, students used their finger on a touchscreen (T), to manipulate the virtual objects. The authors argue that the two input methods result in different kinesthetic experiences that might impact student learning.

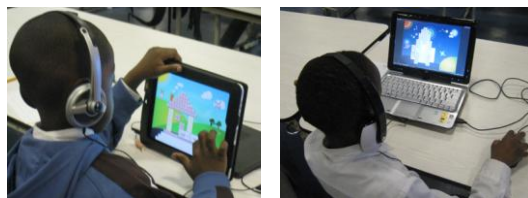


Figure 2. Using *Puzzle Blocks* with either a finger on a screen or a computer mouse

Data Analysis

To measure students' learning outcomes, pre-, mid- and post-tests scores were analyzed using a Profile Analysis. Learning outcomes between the pre-test and mid-test, the pre-test and post-test, and the mid-test and post-test were compared between all four experimental groups. The impact of the two factors, the absence or presence of audio narration (A vs. NA), and the two input devices (M vs. T), were also examined.

Results

Learning Outcomes

The mean scores of participants' learning outcomes from pre-test to mid-test, and pre-test to post-test, and mid-test to post-test for each group are presented in Table 2.

Table 2: Learning Outcomes by Group

Group	Pre- to Mid-Tests		Pre- to Post-Test		Pre- to Post-Test	
	M	SD	M	SD	M	SD
A-T (N = 15)	20.700 (61%)	8.261	28.067 (83%)	6.543	7.367 (22%)	7.965
A-M (N = 14)	19.893 (59%)	6.625	23.464 (69%)	6.843	3.571 (11%)	4.437
NA-T (N = 15)	15.567 (46%)	7.766	21.767 (64%)	7.805	6.200 (18%)	6.716
NA-M (N = 16)	14.563 (43%)	8.828	18.125 (53%)	9.141	3.563 (10%)	5.961

On the mid-test, there was a marginally significant difference among the groups' scores, $F(3, 56) = 2.474$, $p = .071$. The A-T group had the highest mean score increase from pre-test to mid-test ($M = 20.700$, $SD = 8.261$) and the NA-M group had the lowest mean increase ($M = 14.563$, $SD = 8.828$). From the pre-test to the post-test, the A-T group had the highest mean score increase ($M = 28.067$, $SD = 6.543$) and the NA-M group showed the lowest mean score increase ($M = 18.125$, $SD = 9.141$). Differences between the groups' score increases from pre- test to post-test were significant, $F(3, 56) = 5.025$, $p = .004$. Lastly, the groups' score increases from mid-test to post-test were examined. The results show the differences from mid-test to post-test for each group were not statistically significant, $F(3, 56) = 1.338$, $p = .271$.

Main Impact of the Auditory and Kinesthetic Modalities

When the main impact of the two factors on students' learning outcomes was examined, the results reveal that the presence of audio narration led to significantly higher learning outcomes on the mid-test, $F(1, 56) = 6.941$, $p = .011$, and significantly higher learning outcomes on the post-test, $F(1, 56) = 9.272$, $p = .004$, compared to no audio narration. However, the presence of audio narration was not a significant factor between the mid-test and post-test, $F(1, 56) = .125$, $p = .725$. On the other hand, the kinesthetic modality was not a significant factor on students' learning outcomes between pre-test and mid-tests, $F(1, 56) = .363$, $p = .549$. However, it was significant factor between pre-test to post-test, $F(1, 56) = 5.284$, $p = .025$. Finally, it was marginally significant on students' learning outcomes between mid- to post-tests, $F(1, 56) = 3.756$, $p = .058$.

Conclusion

The purpose of this study was to systematically test the design of a modern virtual manipulative environment that provides young learners with visual, aural, and kinesthetic interactions related to a math concept and how such multimodal interactions might impact learning. The results show that the type of multimodal interaction afforded by the virtual manipulative environment impacted learning outcomes as measured by paper-based tests. Participants' aural and kinesthetic experience seemed to influence what was learned. However, the impact of the aural and kinesthetic experience seemed to influence learning in different ways and at different points in the ten-session experiment.

After five sessions (mid-test) with the virtual manipulative environment, the presence of audio narration was a significant factor that helped students learn the concept of multiplication. Furthermore, after ten sessions (post-test), the presence of audio narration remained a significant predictor of learning. The kinesthetic experience also impacted student learning, but in different ways. After ten sessions (post-test) controlling the virtual manipulatives with a touchscreen resulted in significantly higher learning outcomes compared to controlling the manipulatives with a computer mouse. This was not the case after five sessions with the software.

Discussion and Scholarly Significance

From a theoretical perspective, the findings support the notion that rich perceptual experiences may promote perceptually-rich mental simulations, which in turn, may lead to better student learning and understanding (Black, Segal, Vitale, & Fadjo, 2011). However, more research is needed to understand what constitutes a rich perceptual experience in a digital environment. There is much to learn in terms of how such experiences should be implemented in order to optimize learning without overwhelming human cognitive resources. In terms of this study, finding that varied kinesthetic experience seems to influence student learning is especially intriguing given the traction of embodied cognition theories and the emergence of innovative perceptual and tangible user interfaces.

In conclusion, this study illustrates the potential of technology to augment, enhance or build-upon traditional instructional interventions in the domain of math. Although further research is needed to confirm the study's findings, and the limited sample size limits their generalizability, the work presented here should encourage educators, game designers, and researchers to extend their understanding of the role multimodal interaction in learning.

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