The Role of Modality in Virtual Manipulative Design

Seungoh Paek
Teachers College
Columbia University
525 West 120th St.
New York, NY 10027 USA
sop2102@columbia.edu

John Black
Teachers College
Columbia University
525 W 120th St.
New York, NY 10027 USA
black@tc.columbia.edu

Dan Hoffman
Teachers College
Columbia University
525 W 120th St.
New York, NY 10027 USA
dlh2109@columbia.edu

Charles Kinzer
Teachers College
Columbia University
525 W 120th St.
New York, NY 10027 USA
kinzer@tc.columbia.edu

Antonios Saravanos
Teachers College
Columbia University
525 W 120th St.
New York, NY 10027 USA
as2374@columbia.edu

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Abstract
The current study examines aspects of multimedia design in virtual learning environments. It compares touch and mouse input methods in conjunction with audio and visual feedback in an effort to improve young children's math learning. Fifty-nine (N=59) second grade students played Puzzle Blocks (PBs), a virtual manipulative designed to introduce students to the concept of multiplication through repetitive addition. All participants showed significant learning outcomes after playing PBs for five sessions. The results show that having auditory feedback is a more influential factor than input method. Implications are discussed.

Keywords
Multimedia learning environments, virtual manipulatives, design principles, children.

ACM Classification Keywords
H5.2 [Information interfaces and presentation]: User Interfaces.

General Terms
Design, Experimentation, Human Factors.

Introduction

Physical manipulatives, traditionally designed for hands-on, sensory experiences, are popular classroom tools. However, such manipulatives often result in rote learning outcomes leaving students unable to link their physical actions to the underlying math concepts. More recently, virtual manipulatives have been developed to address the limitations of traditional physical manipulatives. This study investigates how virtual manipulatives can be designed to resolve the challenge of rote learning, ultimately improving young children's math learning. The authors argue that a properly designed multimedia learning environment can support young children in linking their physical actions with (virtual) manipulatives to the relevant math concept, emphasizing the relationship between concept and procedure. To do this, the study investigates how multi-sensory (visual, auditory, and kinesthetic) interactions and feedback interact to impact young children's learning.

Background Physical Manipulatives

The idea that physical objects can help young children learn has a long, well-argued path in educational theory. For example, as early as 1895, Froebel developed the idea of object "gifts" and emphasized children's playing with objects for cognitive and social development [5]. Montessori developed artifacts emphasizing children's sensory experience with physical objects [8]. Piaget also described that children in the concrete operations stage learn best through concrete objects [11], and Bruner claimed that children need to manipulate concrete images to understand abstract concepts [4]. With this theoretical backing, many studies have shown that manipulatives assist students' understanding of mathematics and increase their math achievement [12, 13]. Even with such encouraging findings, however, some researchers caution that manipulatives do not guarantee success [2, 3, 9] since students learn in a rote manner [6, 15] and are not able to link their actions with the objects to the abstract symbols they represent [16].

Virtual Manipulatives

Many researchers claim that virtual manipulatives are promising tools for improving students' mathematical thinking [9]. A virtual manipulative is defined as an interactive, Web-based visual representation of a dynamic object that presents opportunities for constructing mathematical knowledge [10]. Moyer et al. [10], describe the advantageous properties of virtual manipulatives: availability regardless of time and place, diverse manipulations in terms of changing color, shape, size, efficiency of managing them, etc. These benefits, although helpful in their own right, do not address the main limitations of physical manipulatives mentioned above. Thus, this study attempts to design an improved virtual manipulative that specifically addresses the limitations of physical manipulatives by leveraging the strengths of digital implementation.

The Modality Principle in Multimedia Learning

Evidence suggests that working memory may consist of multiple processors [1] frequently associated with separate processing of visual-spatial and language-based material [7]. In a learning context, the modality principle states that people learn better from graphics and narration than graphics and printed text because presenting some information in a visual mode and other information in an auditory mode can expand effective working memory capacity [7]. Given this finding, it is likely that virtual manipulatives designed to take advantage of both the auditory and visual channels will be more effective than virtual manipulatives that rely on a single mode. However, it is not known whether the addition of a third modality, in this case the physical/kinesthetic mode, made possible through touch-screen input devices, will enhance or hinder the learning outcomes predicted by the modality principle.

Description of Study

To explore the role of multiple modalities on learning with virtual manipulatives, a game-based virtual manipulative, Puzzle Blocks (PBs), was designed based on multimedia learning principles. The in-game goal of PBs is to reveal a hidden scene by combining groups of blocks. For example, to create a group of six blocks, players build the group by adding two-blocks three times (2+2+2=6). While players move the blocks, they receive visual feedback about the value of the blocks and the sign of the operator. When the building of a group is complete, players are shown the underlying equation including both factors, the equal sign, and the product (e.g. 2x3=6). In addition to visual feedback, PBs can also provide auditory feedback. When present, the audio feedback is played at the same time as the visual feedback, providing a one-to-one reinforcement of the information shown visually. In other words, when a user touches a block of two, the word "2" is presented visually and a narrator says "two." When a user moves a block of two repeatedly, the display shows a visual count of how many times the blocks have been moved while a narrator counts the moves aloud. An adult male with a baritone voice recorded the audio narration in English. Three non-verbal sound effects were used in PBs. These sound effects play throughout PBs, with or without the presence of verbal auditory feedback. The sound effects play whenever players pick up or drop a block, as well as when they dismiss the visual feedback.

By being exposed to the value of the blocks through both the visual and auditory channels, participants might be able to make the connection between the blocks, their actions, and the underlying mathematical concepts of grouping and multiplication. How they move the blocks, whether directly on a touch-screen, or indirectly with a traditional computer mouse, may also impact learning outcomes by mediating the other modalities.

For this study, PBs introduced the two times table which had five levels. Each level was designed to emphasize a part of the multiplication equation (i.e. a factor, the product, etc.). The levels are carefully crafted to scaffold the learning experience as the player is gradually introduced to multiplication.

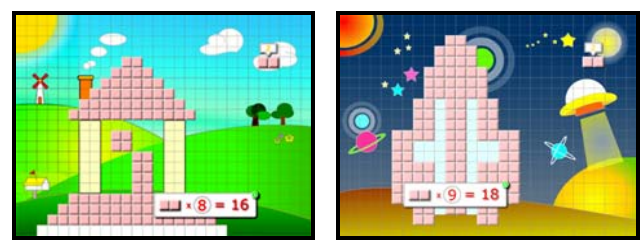

Figure 1. The Puzzle Blocks Interface: Level 2 (left) & Level 3 of the Two Times Table.

Methodology

Fifty-nine (N=59; 18 male, 41 female) second grade students from New York public and charter schools participated in the study. The concept of multiplication had not been formally introduced to the students.

Instruments and Measures

Prior to playing PBs, students took a pre-test examining their knowledge of addition and multiplication. After the pre-test, students who demonstrated an understanding of multiplication were excluded from the study. The remaining fifty-nine students were randomly assigned to six groups based on type of in-game feedback and input method. For example, students in the V-A-DT group received visual and auditory feedback and manipulated the on-screen blocks using a touch screen (iPad). Students in the V-A-IT group also received visual and auditory feedback, but manipulated the on-screen blocks using a traditional computer mouse. Students in the V-NA-DT group received visual, but no audio, feedback while using a touch screen, whereas the V-NA-IT group received visual, but no audio, feedback while using a computer mouse. Finally, two control groups (NV-NA-DT and NV-NA-IT) were included in which students received no feedback (audio or visual) but still manipulated the blocks using one of the two input methods (DT or IT).

	Direct Touch Experience	Indirect Touch Experience
Visual & Auditory Feedback	V-A-DT (N=13)	V-A-IT (N=11)
Visual & No Auditory Feedback	V-NA-DT (N=11)	V-NA-IT (N=12)
No Visual & No Auditory Feedback (control)	NV-NA-DT (N=6)	NV-NA-IT (N=6)

Table 1. Number of participants by experimental group.

Students in all groups played PBs for five sessions focusing solely on the two times table. These sessions took place over a three-week period. In each session, students played multiple levels within the two times table and each play-session lasted approximately 20 minutes. After the five play sessions, students took a paper-based post-test. This post-test was identical to the pre-test, although the order of the items was randomized. The test was composed of questions examining students' visualizations of equations, math fact recall, understanding of concepts, and transfer knowledge- all related to multiplication.

Results

To examine students learning outcomes, a paired-samples t-test was conducted. The analysis yielded a significant difference between the pre- and post-test ($t = 11.825$, $p < .001$). Thus, the results show that students gained knowledge of multiplication by playing PBs. Paired samples t-tests by group found that all groups had statistically significant differences between pre- and post-test scores.

Group N		Mean differences between Pre & Post	s.d.
V-A-DT 13		21.615	8.142
V-A-IT 11		21.045	6.966
V-NA-DT 11		13.318	7.757
V-NA-IT 12		14.292	9.820
NV-NA-DT 6		3.667	.558
NV-NA-IT 6		3.583	1.25

Table 2. Difference between pre- and post-test scores by group.

An analysis of variance (ANOVA) was then conducted to investigate the learning outcomes between groups. The result of the ANOVA revealed significant differences [$F(5,53) = 9.042$, $p < .001$].

To investigate where the significance exists among the groups, a post-hoc least significant difference (LSD) test was conducted. The results show no significant difference between the V-A-DT and V-A-IT groups. There was a significant difference between V-A-DT and V-A-IT and the other groups. Furthermore, there was no significant difference between V-NA-DT and V-NA-IT. Significant differences between V-NA-DT and V-NA-IT and NV-NA-DT and NV-NA-IT were also found.

	V-A-DT	V-A-IT	V-NA-DT	V-NA-IT	NV-NA-DT	NV-NA-IT
V-A-DT	1.000 .	854 .	009*	.018*	.000*	.000*
V-A-IT	.854	1.000 .	020*	.036*	.000* .	000*
V-NA-DT	.009* .	020*	1.000 .	758	.014*	.014*
V-NA-IT	.018* .	036*	.758	1.000 .	007*	.006*
NV-NA-DT	.000* .	000*	.014* .	007*	1.000 .	985
NV-NA-IT	.000* .	000*	.014* .	006*	.985	1.000

Table 3. Results of multiple comparisons of LSD test

Conclusion

The results suggest that playing PBs led to students' learning of multiplication, as measured by their understanding of the two times table. Compared to the groups in which visual and auditory feedback was provided (V-A-DT, V-A-IT, V-NA-DT, V-NA-IT) the control groups (NV-NA-DT & NV-NA-IT) showed significantly lower learning outcomes. Students in the groups that received auditory feedback *and* visual feedback (V-A-DT & V-A-IT) showed significantly higher learning outcomes than students in the groups where only visual feedback was provided (V-NA-DT & V-NA-IT). Meanwhile, the third-modality of input method did not seem to produce significant differences between groups. Thus, it can be concluded that, regardless of input method, having visual feedback, especially visual feedback in tandem with audio feedback, is crucial for learning with virtual manipulatives.

Why is audio feedback so important? One possibility is offered by Szalma's [14] notion that audio feedback places less emphasis on bodily orientation because the user is usually closely linked to the source of the stimulation, often through headphones. Visual feedback, on the other hand, is more dependent on the physical orientation of the user, and therefore more susceptible to interruption by head or eye movements.

Implications

This study suggests that virtual manipulatives, designed with multimedia learning principles in mind, can be effective environments for young children's math learning. The results demonstrate the potential of virtual manipulatives to act as a tool for self-guided instruction through the use of careful scaffolding and level design. Furthermore, it is promising to observe that students were able to link their physical in-task manipulations of virtual blocks to the underlying mathematical concept of multiplication as repetitive addition. Encouragingly, although students were only exposed to the two times table, evidence suggests that the students were able to transfer the knowledge to times tables they had yet to experience. In conclusion, the findings of the study highlight the importance of exploring all aspects of multimedia design. Often, the possibilities of multimedia learning environments are overlooked due to an over emphasis on visual design. Although important, the current study underscores the importance of looking at other modalities (auditory, kinesthetic) and how they can be leveraged and combined to improve the learning experience of students.

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