Education Tech Research Dev
DOI 10.1007/s11423-016-9427-8

RESEARCH ARTICLE

Perceptual factors and learning in digital environments

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Abstract The purpose of this study was to examine if student understanding of new material could be promoted by manipulating the perceptual factors experienced at the time of learning. It was hypothesized that the thematic relevance of perceptual factors would be a significant contributor to learner understanding. To test this hypothesis, one hundred seventy-three (n = 173) first and second grade students with limited prior knowledge were introduced to multiplication using a virtual manipulative environment. While interacting with the environment, participants encountered varied levels of thematic relevance in the audio and bodily-kinesthetic modalities. The audio perceptual factor varied what learners heard while the kinesthetic perceptual factor varied how learners moved. The results show that changes in the sensory experience at the time of learning have a "bottom up" impact on learners' ability to process new content. Evidence also suggests that the thematic relevance of perceptual factors mediates learner understanding in different ways over different time scales. The study concludes with a discussion of design-related issues and suggestions for future research.

Keywords Multimedia learning · Modality · Virtual manipulatives · Interactivity · Perceptual factors · Thematic relevance · Perceptual richness

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Published online: 08 February 2016

Introduction

Understanding how learners interact cognitively and behaviorally with content presented in digital environments is an increasingly important yet complex aspect of education research. Its importance stems from the fact that more digital content is being made available to more students in more contexts (see Collins and Halverson 2009). Its complexity arises from the seemingly infinite combinations of learner, task, and system variables that ultimately shape the "goings-on" between learners and the content with which they interact.

In an effort to contribute to the field's understanding of digital learning, the following work examines the concept of perceptual richness and its potential to mediate learner understanding of content encountered in digital environments. The theoretical backdrop of this examination is the growing body of evidence suggesting cognition is embodied—the view that human cognition has deep roots in sensorimotor processing (Wilson 2002). Drawing on this perspective, we establish two premises to ground our study. The first premise is that perceptual richness, defined as converging sensorimotor inputs, plays an important role in retaining and retrieving past events from long-term memory—a premise with powerful implications for the design of learning environments. The second premise is that perceptual richness emerges from individual perceptual factors—sensory or motor experiences intentionally embedded in learning environments to support relevant cognitive processing.

These premises lead us to the central question of the study: Is it possible to promote understanding of new material by manipulating the perceptual factors experienced at the time of learning? We hypothesize that perceptual factors can have a measurable "bottom-up" impact on learner understanding, a view consistent with embodied cognition. In particular, we argue that a perceptual factor's thematic relevance is a major determinant of its ability to provide "conceptual leverage" (Resnick 2002, p. 35) that supports learners.

To test our hypothesis about the thematic relevance of perceptual factors, a study was conducted in which young children were introduced to multiplication using a digital environment. While interacting with this environment, the children experienced varying levels of thematic relevance through two perceptual factors: one in the auditory modality and the other in the kinesthetic modality. The results provide evidence that even subtle variation in the thematic relevance of perceptual factors mediated participants' learning outcomes but in different ways. We end with a detailed examination of the findings followed by a discussion of the implications perceptual factors and thematic relevance have on the design of future learning environments.

Literature review

In recent years there has been increased interest in the theories of embodied cognition. These theories propose close links between sensory and motor systems and cognition (Barsalou et al. 2003; Gallese and Lakoff 2005; Wilson 2002). Although there are different perspectives on embodied cognition (Wilson 2002), a central idea is that the body and the senses play an important role in "contributing to and shaping ongoing cognitive activity" (Alibali 2005, p. 309).

Education researchers have used this theoretical development to examine the potential of embodiment to act as a force that promotes learning (Alibali and Nathan 2012; Lindgren and Johnson-Glenberg 2013). The embodied learning approach studies "instructional methods that incorporate the body" (Lindgren and Johnson-Glenberg 2013, p. 445). The purpose of these instructional methods is to leverage the body and the senses to promote understanding and improve learning outcomes. For example, gestures and other body movements enacted in traditional, non-digital environments have been studied for their relationship to learning and memory (Goldin-Meadow et al. 2009). Other forms of physicality have been studied in a range of digital environments including Kinect-based embodied learning systems (Chao et al. 2013; Homer et al. 2014; Sheu and Chen 2014) and whole-body metaphor-based simulations (Lindgren and Johnson-Glenberg 2013). What this diverse body of work has in common is a belief in the centrality of the body and the senses in influencing cognition.

An important concept to emerge out of embodiment research is *perceptual richness*. Perceptual richness is rarely defined but has been used to describe various learning materials for decades (Carlson and Zmud 1999; Jenkins 1968; Kaminski et al. 2008; Swaak and De Jong 2001). Lindgren and Johnson-Glenberg (2013) refer to perceptual richness as "converging inputs" from engaged sensorimotor systems. This characterization is reminiscent of earlier work in media richness theory which characterized 'richer' media as having multiple cues capable of facilitating meaning (Daft et al. 1987, p. 358). More recent work in multimedia learning has focused on working memory and the assumption that visual and auditory information is processed separately (Sweller et al. 1998). Empirical work in this area has shown learners benefit when information is presented across audio and visual modalities (Ginns 2005; Mayer and Moreno 2003). Although these ideas stem from different theoretical traditions, they share an appreciation for the role of perceptual richness, and its constituent modalities, in our ability to make sense of the world.

Other researchers have looked at the relationship between perceptual richness and specific aspects of cognition. For example, St-Laurent et al. (2014) described perceptual richness as the *retrieval* of rich sensory-based memory details. They presented evidence that perceptual richness plays an important part in the "retention, retrieval, and assemblage of multimodal memory elements into vivid recollective experiences" (p. 572–273). Another example can be found in the work of Black et al. (2011) who examined the role of perceptual richness in digital learning environments. Drawing on the work of Barsalou (1999), Black and colleagues argued that richer perceptual experiences led to better student understanding due to their potential to facilitate mental perceptual simulations (p. 200). To support this claim, they cited related work with sensory-enriched environments involving direct manipulation interfaces (Chan and Black 2006) and haptic augmented simulations (Han and Black 2011).

The literature reviewed thus far suggests that cognition is grounded in sensory and motor experience and that perceptual richness can mediate memory and understanding. We now turn to the question of *how* perceptual richness might be embedded into digital learning environments. To do this, it is useful to distinguish between the cognitive and behavioral interactions learners experience while engaging with digital environments.

Cognitive interactions are the result of mental processes. Examples of such processes include selecting relevant information, mentally organizing it, and integrating it with existing knowledge (Moreno and Mayer 2007, p. 312). These individual processes involve complex interactions that take place between the external representations provided by the system and the internal (mental) representations constructed by learners (Schnotz and Lowe 2003, p. 118). These interactions are essential to the learning process and, ideally, alter long-term memory. As Kirschner et al. (2006) wrote, "If nothing has changed in long-term memory, nothing has been learned" (p. 77).

In addition to cognitive interactions, learners also experience behavioral interactions. Behavioral interactions constitute what leaners do physically as they interact with to-be-learned content. Such interactions can be relatively passive in nature such as watching an animation or listening to a narration. On the other hand, behavioral interactions may be more physical in nature as learners push buttons or manipulate variables (see Kennedy 2004). Moreno and Mayer (2007) described the range of possible behavioral interactions as a "continuum" ranging from highly interactive to non-interactive (p. 311). In the embodied learning literature, behavioral interactions are sometimes referred to as "somatic actions" (Abrahamson and Lindgren 2014) or "action experiences" (Kontra et al. 2012). Regardless of what they are called, theories of embodied cognition suggest behavioral interactions should no longer be incidental components of digital environments but rather the result of careful instructional choices intended to support learning.

We delineate between cognitive and behavioral interactions in an effort to frame our thinking about how to incorporate perceptual richness into digital learning environments. Because behavioral interactions involve the body and the senses, we refer to them as *perceptual factors*—sensory or motor experiences incorporated into learning environments to support relevant cognitive processing. Ideally, each perceptual factor will provide "conceptual leverage" (Resnick 2002, p. 35) that promotes understanding of the to-be-learned content. For there to be leverage, however, perceptual factors need to be carefully designed. Nathan (2012) proposes that a grounded relationship between direct physical and perceptual experience and the abstract concept is necessary in order to help learners (p. 139). But what makes a perceptual factor more or less likely to "ground" abstract concepts?

While studying how learners construct mental models from visual displays, Lowe (1999) found two important design characteristics: perceptual salience and thematic relevance. In terms of perceptual salience, he found that learners tended to extract information based on its relative "perceptual conspicuity" (p. 241). In other words, learners switched their attention to obvious visual features regardless of whether or not they were relevant to the to-be-learned concept. While Lowe's work focused on visual information it is reasonable to believe perceptual conspicuity applies across sensory modalities. For example, one way to alter a gesture's conspicuity might be to change its magnitude (e.g., fine motor vs. gross motor). In short, perceptual factors might be used to emphasize certain types of information by being made more or less conspicuous.

In addition to being perceptually conspicuous, Lowe suggested perceptual factors should be thematically relevant in order to ground concepts. In later work, Boucheix and Lowe (2010) characterized thematic relevance as concerning the components and relationships that explain the causal chains of a system (p. 124). In other words, for a perceptual factor to be effective in grounding a concept it should draw on sensory or motor experiences that highlight essential components or relationships of the target concept.

In their work on graphics portraying metaphorically spatiovisual content, Tversky et al. (2002) hit upon a possible description of how sensory or motor experiences might ground concepts. They wrote of the "cognitive correspondences" that can take place between mental spaces and real ones (p. 249), between cognitive interactions and behavioral ones. The concept of cognitive correspondences is useful in this context: perceptual factors can be considered thematically relevant, and therefore more likely to ground relationships, if they correspond cognitively to the to-be-learned content. In this way, bodily or external experiences might enrich mental representations, matching what designers want students to encode into memory (Rapp and Kurby 2008, p. 30).

Taken together, this brief review began by summarizing the embodied cognition perspective. It further described evidence that perceptual richness may be an important characteristic of environments designed to support learning. It went on to reason that perceptual richness is made up of individual perceptual factors that help learners ground abstract concepts in bodily experience. The review concluded by positing that two important aspects of perceptual factors include perceptual conspicuity and thematic relevance. In the next section, we describe a study designed to examine the impact of thematically relevant perceptual factors on student learning.

Data and methods

Research design

To examine the role of perceptual richness in promoting student understanding, a digital environment was designed to introduce young children to multiplication. This environment allowed the researchers to systematically vary the thematic relevance of two perceptual factors while keeping all other aspects of the learning experience the same.

The first perceptual factor varied the audio experience. This factor altered what learners *heard* while interacting with the environment. Two levels of thematic relevance were made possible: less thematically relevant audio (LA) and more thematically relevant audio (MA). The less thematically relevant audio was designed to be perceptually conspicuous but of no thematic relevance. This was accomplished through the use of non-verbal sound effects similar to those found in casual videogames. In other words, it possessed no semantic relation to the target concept (multiplication). In contrast, the more thematically relevant audio was designed to be perceptually conspicuous and thematically relevant. This was accomplished by using brief verbal voiceovers that "read" aloud on-screen mathematical notation. For example, if the equation $2 \times 3 = 6$ was displayed visually, a narrator would say, "two times three equals six." The more thematically relevant audio did not provide additional information beyond what was available visually.

While both levels of the audio-related perceptual factor were delivered through the audio channel and did not differ in perceptual salience, they were designed to differ in terms of their thematic relevance and, therefore, to mediate learner understanding of multiplication. Specifically, it was hypothesized that the more thematically relevant audio would offer greater cognitive correspondence between the audio sensory experience and the target concept, ultimately resulting in a measurable learning advantage for students.

The second perceptual factor varied the kinesthetic experience. This factor altered how learners *moved* (physically) while interacting with the environment. Two levels of thematic relevance were made possible: less thematically relevant movements (LM) and more thematically relevant movements (MM). The less thematically relevant movements were operationalized as manipulations of on-screen objects using a cursor controlled by a traditional computer mouse. The more thematically relevant movements were operationalized as manipulations of on-screen objects using a finger on a touchscreen.

While both levels of the kinesthetic-related factor were experienced through the kinesthetic channel and did not differ in perceptual salience, they were designed to differ in terms of their thematic relevance and, therefore, to mediate learner understanding of multiplication. Specifically, it was hypothesized that the more thematically relevant movements would offer greater cognitive correspondence between the bodily-kinesthetic experience and the target concept, ultimately leading to a measurable learning advantage for students.

With the perceptual factors defined, three research questions were posed. The first research question asked if the thematic relevance of the audio perceptual factor would impact novice learners' understanding of multiplication introduced in a digital learning environment. The second research question asked if the thematic relevance of the kinesthetic perceptual factor would impact novice learners' understanding of multiplication introduced in a digital learning environment. A third research question focused on the temporal aspects of the perceptual factors asking if the amount of time learners experienced each factor would mediate their impact on student understanding of multiplication.

Participants

One hundred seventy-three (n = 173) first and second grade students from public and parochial schools in a large Northeast city participated in the study. To qualify for participation, students had to demonstrate proficiency with addition and minimal prior knowledge of multiplication. Prior knowledge of addition and multiplication was assessed using two paper-based tests (described below). Participants who met the requisite requirements were randomly assigned to one of six groups: four experimental and two control.

The four experimental groups were based on a 2 × 2 design: audio perceptual factor (MA, LA) × kinesthetic perceptual factor (MM, LM). The control groups used a non-educational version of the software (see Research Software for details). Two control groups were required to match the two levels of the kinesthetic perceptual factor. One control group used less thematically relevant movements (C-LM) while the other group used more thematically relevant movements (C-MM). As it was unlikely participants in the control groups would learn anything about multiplication from the non-educational version of the software, the number of participants was kept low for ethical reasons. Table 1 summarizes the six groups.

Procedure

The intervention began by introducing participants to the research team. All participants then completed two prior knowledge tests assessing their proficiency with addition and multiplication. If students demonstrated proficiency with addition and minimal prior knowledge of multiplication, they qualified to participate and were assigned a group.

Table 1 2 × 2 experimental design with control groups

		Less thematically relevant movement (LM)	More thematically relevant movement (MM)
Experimental groups	Less thematically relevant audio (LA)	LA + LM *n = 32*	LA + MM *n = 35*
	More thematically relevant audio (MA)	MA + LM *n = 34*	MA + MM *n = 39*
Control groups	–	C + LM *n* = 18	C + MM *n* = 15

Participants were then given a demonstration of the software. Ample time was provided to test the software, try on headphones, and ask questions.

After the introduction, all participants followed an identical procedure consisting of ten sessions that took place over a two-week period. Each session lasted approximately 20 min and involved participants working individually with their assigned version of the software. The first five sessions (1–5) focused solely on the two times table. The two times table was chosen because it involves the "many-to-one correspondence" (Clark and Kamii 1996, p. 43) inherent in multiplicative thinking but difficult to "see" in the zero and one fact families. At the end of the fifth session, an electronic mid-test was administered. The purpose of the mid-test was to assess participants' understanding of multiplication after five sessions or approximately 100 min (5 sessions $\times$ 20 min) of exposure to the perceptual factors.

The second five sessions (6–10) focused solely on the three times table. The three times table was chosen as a natural progression from the two times table, a change that allowed participants to continue exploring the many-to-one correspondence involved in multiplicative thinking. After the tenth and final session, participants were given an electronic post-test. Like the mid-test, the post-test was designed to assess participants' understanding of multiplication after ten sessions or approximately 200 min (10 sessions $\times$ 20 min) of exposure to the perceptual factors.

Participants were limited to the two and three times tables for experimental purposes. This design allowed the researchers to examine if participants could apply any new knowledge gained from interacting with the two and three times tables in the digital environment to solve novel multiplication questions from different times tables on the mid-test and post-test. Another design choice was to present the same multiplication questions in the same order to all participants, an effort to ensure internal consistency between groups.

The post-test marked the end of the intervention. Students were thanked for their participation and given a certificate congratulating them on their hard work. All participants completed the study.

Materials

The materials used in the study consisted of paper-based and electronic instruments developed by the researchers. Each instrument and its corresponding measures are described below.

Addition prior knowledge assessment

This assessment was designed to measure participants' prior knowledge of addition—a prerequisite skill for multiplication. The assessment was paper-based and consisted of two sections. The first section contained twelve addition questions consisting of single-digit (e.g., $9 + 6 = ?$) and two-digit (e.g., $13 + 19 = ?$) fill-in the blank problems. The second section consisted of two repeated addition problems (e.g., $2 + 2 + 2 = ?$). All questions were taken from popular elementary mathematics textbooks and were worth a single point. Pencils and erasers were provided. No time limit was enforced. The instrument yielded one measure: total correct. The maximum possible score was 14. Participants were deemed proficient with addition if they obtained a score of fifty percent or higher.

Multiplication prior knowledge assessment

This assessment was designed to measure participants' prior knowledge of multiplication—the target concept of the study. The assessment consisted of two sections. The first section required participants to distinguish between the addition (+) and multiplication (×) operators. This was accomplished by having research assistants sit with participants, point to a multiplication equation (e.g., $4 \times 2 = 8$), and ask, "Can you read this math problem to me?" If participants were able to read the equation, correctly articulating the multiplication operator (e.g., four *times* two), they proceeded to the next section. Participants who did not say, "times", "multiplied by", or an equivalent phrase, were assumed to have no prior knowledge of multiplication. In this case, the assessment was stopped and participants were assigned a pre-test score of zero, leaving them eligible for the study.

Participants who recognized the multiplication operator were asked to complete the second part of the assessment. This section included twelve single digit multiplication problems (e.g., $4 \times 3 = ?$). The questions from this section were taken from popular elementary mathematics textbooks and were worth a single point each. Pencils and erasers were provided. No time limit was enforced. The instrument yielded one measure: total correct. The maximum possible score was 12. Participants were deemed eligible to participate if they scored fifty percent or below.

Research software

The researchers developed the digital learning environment used in the study. The environment was designed to introduce children to the concept of multiplication which was conceptualized as "performing operations on collections a certain number of times" (Lakoff and Núñez 2000, p. 60). In this case the "collections" were virtual manipulatives—interactive visual representations of dynamic objects that present opportunities for constructing mathematical knowledge (Moyer et al. 2002). A virtual manipulative environment was chosen for the study due to its high level of interactivity and ability to connect dynamic images with abstract symbols (Reimer and Moyer 2005). The dynamic images in this context were interactive blocks and the abstract symbols were standard mathematical notation.

While practicing times tables in the environment, participants were required to complete five sequential levels. These levels presented numerous multiplication-related tasks involving factors and products. As tasks were completed, colorful puzzle pieces were revealed one-by-one to indicate progress and help motivate participants. Figure 1 shows the progression of a level from the two times table.

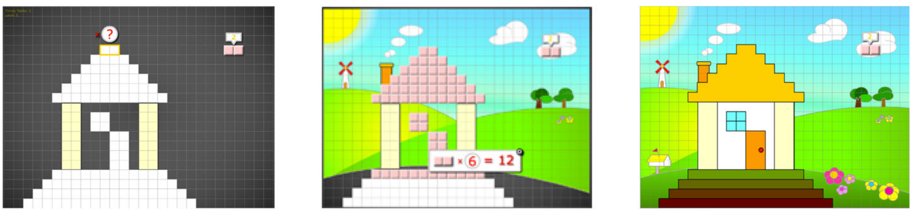

Fig. 1 Colorful 'puzzle' pieces were revealed one-by-one as learners completed multiplication-related tasks involving interactive blocks

Visually, the virtual manipulative environment consisted of graphic and symbolic representations. The graphic representations took the form of interactive blocks that could be stacked and combined in various ways. The symbolic representations took the form of traditional mathematics notation. Mathematical notation was used sparingly for the experimental groups and not at all for the control groups. When both types of representations were displayed, the mathematical notation was spatially and temporally aligned to the corresponding graphics (i.e., the blocks). Figure 2 shows an example of the software showing graphic and symbolic representations simultaneously.

In terms of interactivity, all tasks required basic 'drag and drop' manipulations of on-screen blocks and numbers (blocks only for the control groups). For instance, while practicing the two times table, participants might be required to move blocks of two units three times to build a group of six units ($2 \times 3 = 6$). As each block of two units is moved and dropped onto its target location, participants are shown graphic and symbolic feedback. The graphic feedback shows the (initially empty) larger group filling-up two units at a time. The symbolic feedback shows the resulting multiplier in the form of "×1," "×2", "×3" and so on. When a target group becomes full of blocks, a complete multiplication equation appears. Figure 3 shows an example of a full group of six units and the resulting feedback in the form of an equation.

The environment described thus far represents the baseline experience consistent across all versions (experimental and control) of the software. There were, however, important differences in the software depending on the group to which participants were assigned. One of the differences was the level of thematic relevance experienced in the auditory and kinesthetic channels as described in the previous section (see Research Design). Another difference was the platform on which the virtual manipulative environment was deployed. Two platforms were needed because the experiment required two input methods (LM: computer mouse; MM: touchscreen). Therefore, the environment was deployed on laptops and tablets. Despite altering the input method, all other aspects of the platforms were identical including screen resolution (1024×768).

A final notable difference involved the design of the non-educational version of the software used by the control groups. The control versions of the virtual manipulative

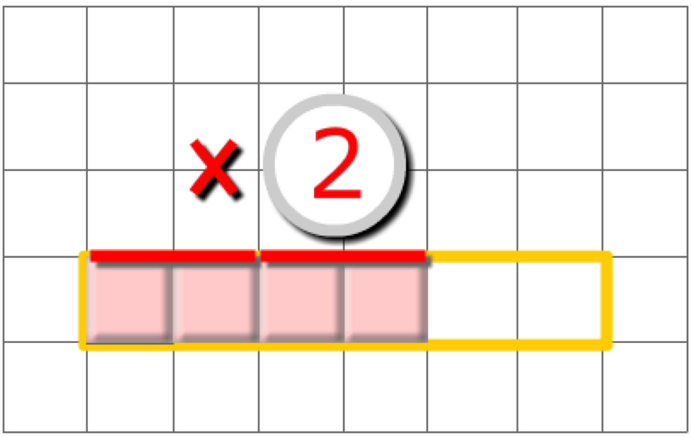

Fig. 2 The virtual manipulative environment presented graphic and symbolic representations to the experimental groups. The control groups were presented graphic representations only

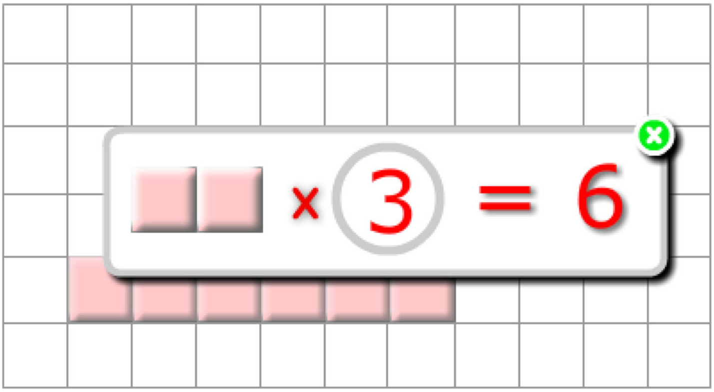

Fig. 3 A complete multiplication equation (2 × 3 = 6) consisting of graphic and symbolic representations

environment involved the same puzzles and 'drag and drop' manipulations as the experimental versions but made no reference to mathematics. Thus, participants made matching physical movements in the same sequence for the same amount of time, but had no exposure to the underlying mathematics. To accommodate the two levels of the kinesthetic perceptual factor, two versions of the control software were used (C-LM, C-MM).

Multiplication mid-test

The purpose of the multiplication mid-test was to assess participant knowledge of multiplication. The test itself was a near transfer task as it was similar to the original learning condition in terms of structure and content (see Royer et al. 2005, p. x). Structurally, the mid-test items looked like the multiplication problems practiced in the virtual manipulative environment, consisting of mathematical notation spatially aligned to corresponding graphics (see Fig. 4). However, the graphics used in the mid-test were static and could not be manipulated.

In terms of content, all twelve items were single digit multiplication questions. Like the prior knowledge assessments, these items were taken from popular elementary

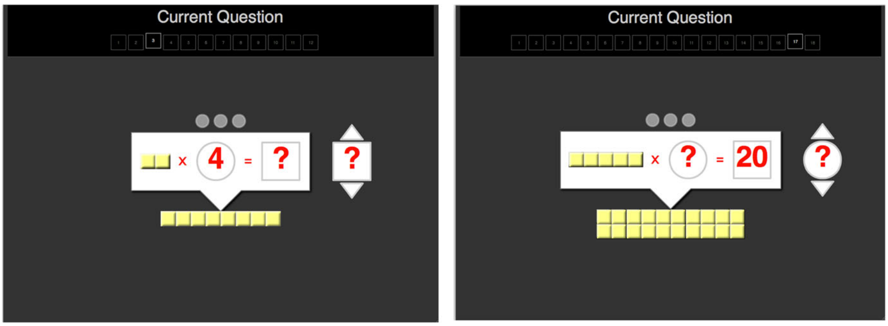

Fig. 4 A studied item (2 × 4 = ?) from the two times table (*left*) and an unstudied problem (5 × ? = 20) from the five times table (*right*). The mid-test and post-test were designed to be near transfer tasks, similar in structure and content to the original learning condition

mathematics textbooks. Half of the items (50 %) asked for a missing factor (e.g., 2 × ? = 8) while the other half (50 %) asked for a missing product (e.g., 2 × 6 = ?). Three of the twelve items (25 %) were from the two times table and were considered "studied" by participants. The remaining nine items (75 %) were considered "unstudied" as they were taken from the three, four, and five times tables. All participants experienced the same items in the same sequence. Table 2 lists the items and the order in which they appeared.

Participants received immediate accuracy feedback after submitting answers on the test. The test allowed participants to attempt every item a maximum of three times. After three incorrect answers, however, the software automatically advanced to the next item or, when appropriate, ended the test. No time limit was enforced and overall progress was displayed on the screen. The test included no audio and participants used the same input method used during the training sessions. The mid-test yielded two measures of accuracy: the number of correct *studied* items (maximum of three) and the number of correct *unstudied* items (maximum of nine). It also included two measures of efficiency: the number of attempts per *studied* item (maximum of three) and the number of attempts per *unstudied* item (maximum of three). Cronbach's alpha for the twelve items on the mid-test was .845.

Multiplication post-test

The multiplication post-test was identical to the mid-test in design and functionality; however, it contained eighteen single-digit multiplication questions instead of twelve. Ten of the items (56 %) asked for a missing factor (e.g., 2 × ? = 8) while the remaining eight (44 %) asked for a missing product (e.g., 2 × 6 = ?). Ten of the items (56 %) were from

Table 2 Multiplication questions included in the mid-test and post-test

Mid-test						Post-test					
	2	×	?	=	6		3	×	3	=	?
	2	×	?	=	12		3	×	?	=	15
	2	×	4	=	?		3	×	6	=	?
*	3	×	3	=	?		3	×	?	=	12
*	3	×	?	=	15		3	×	?	=	3
*	3	×	6	=	?		2	×	?	=	6
*	4	×	?	=	12	*	4	×	?	=	12
*	4	×	?	=	16	*	5	×	2	=	?
*	4	×	1	=	?		2	×	?	=	16
*	5	×	2	=	?		2	×	4	=	?
*	5	×	3	=	?		2	×	?	=	12
*	5	×	?	=	20	*	4	×	?	=	16
						*	5	×	3	=	?
							2	×	5	=	?
						*	5	×	1	=	?
						*	4	×	?	=	8
						*	5	×	?	=	20
						*	4	×	1	=	?

* Denotes novel, unstudied multiplication questions

the two or three times tables and were considered “studied” by participants. The remaining eight items (44 %) were considered “unstudied” as they involved content from the four and five times tables. All participants experienced the same items in the same sequence. Table 2 lists the items and the order in which they appeared.

The post-test yielded two accuracy measures: the number of correct *studied* items (maximum of ten) and the number of correct *unstudied* items (maximum of eight). It also included two measures of efficiency: the number of attempts per *studied* item (maximum of three) and the number of attempts per *unstudied* item (maximum of three). Cronbach’s alpha for the eighteen items on the post-test was .947.

Independent variables

The independent variables included two levels of the audio-related perceptual factor and two levels of the kinesthetic-related perceptual factor. The two levels of the audio-related perceptual factor included the less thematically relevant audio (LA) and the more thematically relevant audio (MA). The two levels of the kinesthetic-related perceptual factor included the less thematically relevant movements (LM) and the more thematically relevant movements (MM).

Dependent variables

In total there were eight dependent variables. Four dependent variables came from the mid-test: (1) number of correct studied items, (2) number of correct unstudied items, (3) number of attempts per studied item, (4) number of attempts per unstudied item. Four more dependent variables came from the post-test: (5) number of correct studied items, (6) number of correct unstudied items, (7) number of attempts per studied item, and (8) number of attempts per unstudied item.

Results

A preliminary analysis compared the six groups (4 experimental, 2 control) in terms of their prior knowledge of addition and multiplication. An analysis of variance (ANOVA) found no significant difference between the groups’ prior knowledge addition scores, F (5, 167) = 0.43, p = .825. By design, participants’ scores for prior knowledge of addition were relatively high with a mean of 9.28 (SD = 1.63) out of twelve (77 %). Participants’ scores on the multiplication prior knowledge test were also compared. Again, no significant difference was found between the six groups, F (5, 167) = 0.49, p = .780. As anticipated, the mean score for prior knowledge of multiplication was very low (M = 0.38, SD = 1.21) with the highest score recorded being five out of twelve (41.7 %).

Mid-test results

The purpose of the mid-test was to examine the impact of each perceptual factor on participants’ understanding of multiplication after five sessions with the software. The first step in the mid-test analysis was to compare the experimental groups to the control groups in terms of accuracy. Recall that the mid-test yielded two accuracy scores: the number of correct studied items and the number of correct unstudied items. Comparing the number of correct studied items revealed a significant difference favoring the experimental groups over the control groups: t (35.542) $= -8.34$, $p < .001$. The mean number of correct studied items for the experimental groups was 2.82 ($SD = 0.50$) out of three, whereas the mean for the control groups was 1.27 ($SD = 1.04$). Similar results were found for the number of correct unstudied items, again favoring the experimental groups over the control groups: t (171) $= -9.26$, $p < .001$. The mean number of correct unstudied items for the experimental groups was 6.70 ($SD = 2.12$) out of nine, whereas the mean for the control groups was 2.82 ($SD = 2.35$).

The second step in the mid-test analysis was to compare the experimental groups to the control groups in terms of efficiency. Recall that the mid-test yielded two efficiency scores: the number of attempts per studied item and the number of attempts per unstudied item. Comparing the mean number of attempts per studied item revealed a significant difference favoring the experimental groups over the control groups: t (171) $= 9.87$, $p < .001$. Similar results were found for the number of attempts per unstudied item, again favoring the experimental groups over the control groups: t (171) $= 6.75$, $p < .001$. See Table 3 for details.

Since the experimental and control groups did not differ in terms of prior knowledge, the significant differences reported above can be attributed to the intervention itself as opposed to an unknown external factor. Therefore the subsequent analyses compared the mid-test results of the experimental groups only.

Audio-related perceptual factor at mid-test

A multivariate analysis of variance (MANOVA) found the level of thematic relevance experienced in the audio modality was not a significant predictor of the number of correct studied items or the number of correct unstudied items at mid-test. However, the audio-related perceptual factor was found to be a significant predictor of the mean number of attempts used per studied item: F (1, 136) $= 4.79$, $p = .030$, $\eta_p^2 = .03$. More specifically, participants experiencing the more thematically relevant audio required significantly fewer attempts per studied item ($M = 1.31$, $SD = 0.44$) compared to participants experiencing the less thematically relevant audio ($M = 1.49$, $SD = 0.55$). The audio-related perceptual factor was not a significant predictor of the mean number of attempts per unstudied item. See Tables 4 and 5 for details.

Kinesthetic-related perceptual factor at mid-test

A MANOVA found that the level of thematic-relevance experienced in the bodily-kinesthetic modality varied as a predictor. It was not a significant predictor of the mean number of correct studied items. However, it was a significant predictor of the mean number of correct unstudied items, F (1, 136) $= 12.17$, $p = .001$, $\eta_p^2 = .08$. Participants experiencing more thematically relevant movements scored significantly higher ($M = 7.27$, $SD = 1.87$) than participants using less thematically relevant movements ($M = 6.06$, $SD = 2.21$). In contrast, the kinesthetic-related perceptual factor was not a significant predictor of the mean number of attempts per studied item. However, it was a significant predictor of the mean number of attempts per unstudied item: F (1, 136) $= 9.27$, $p = .003$, $\eta_p^2 = .06$. Participants using the more thematically relevant movements required significantly fewer attempts per unstudied item ($M = 1.81$, $SD = 0.45$) compared to participants using less thematically relevant movements ($M = 2.05$, $SD = 0.46$). See Tables 6 and 7 for details.

Table 3 Means and standard deviations for the number of correct items and the number of attempts per item at mid-test: control groups versus experimental groups

	n	Studied				Unstudied			
		M	*SD*	*t*	*p*	*M*	*SD*	*t*	*p*
Number of correct items[a]									
Cont.	33	1.27	1.04	−8.34	<.001	2.82	2.35	−9.26	<.001
Exp.	140	2.82	0.50			6.70	2.12		
Number of attempts per item[b]									
Cont.	33	2.39	0.59	9.87	<.001	2.53	0.43	6.75	<.001
Exp.	140	1.39	0.50			1.92	0.47		

[a] Max. number of correct studied items is 3; max. number of correct unstudied items is 9

[b] Max. number of attempts per studied and unstudied item was 3

Post-test results

The purpose of the post-test was to examine the impact of each perceptual factor on participant understanding of multiplication after ten sessions with the software. The first step in the post-test analysis was to compare the experimental groups to the control groups in terms of accuracy. Like the mid-test, the post-test yielded two accuracy scores: the number of correct studied items and the number of correct unstudied items. Comparing the number of correct studied items between groups revealed a significant difference favoring the experimental groups over the control groups: $t\ (36.11) = -12.21$, $p < .001$. The mean number of correct studied items for the experimental groups was 9.40 ($SD = 1.41$) out of ten, whereas the mean number of correct studied items for the control groups was 3.42 ($SD = 2.73$). Similar results were found for the number of correct unstudied items, again favoring the experimental groups: $t\ (40.70) = -12.54$, $p < .001$. The mean number of correct unstudied items for the experimental groups was 7.19 ($SD = 1.43$) out of eight, whereas the mean for the control groups was 2.73 ($SD = 1.92$).

The second step in the post-test analysis was to compare the experimental groups to the control groups in terms of efficiency. Like the mid-test, the post-test yielded two efficiency scores: the number of attempts per studied item and the number of attempts per unstudied item. Comparing the number of attempts per studied item between the groups revealed a significant difference favoring the experimental groups over the control groups: $t\ (38.68) = 12.27$, $p < .001$. Similar results were found for the number of attempts per unstudied item, again favoring the experimental groups over the control groups: $t\ (171) = 11.27$, $p < .001$. See Table 8 for details.

Since the experimental and control groups did not differ in their prior knowledge, the significant between-group differences found on the post-test can be attributed to the intervention itself as opposed to an unknown external factor. Therefore the subsequent analyses compared the post-test results of the experimental groups only.

Audio-related perceptual factor at post-test

A MANOVA found the audio-related perceptual factor to be a significant predictor of the number of correct studied items at post-test: $F\ (1,\ 136) = 4.20$, $p = .042$, $\eta_p^2 = .03$.

Table 4 Means and standard deviations for the number of correct items and the number of attempts per item at mid-test: less thematically relevant audio (LA) versus more thematically relevant audio (MA)

	n	Studied		Unstudied		Total	
		M	*SD*	*M*	*SD*	*M*	*SD*
Number of correct items[a]							
LM	67	2.79	0.51	6.64	2.08	9.43	2.22
MM	73	2.85	0.49	6.75	2.17	9.60	2.40
Number of attempts per item[b]							
LM	67	1.49	0.55	1.98	0.43	1.86	0.37
MM	73	1.31	0.44	1.88	0.50	1.73	0.40

[a] Max. number of correct studied items is 3; max. number of correct unstudied items is 9

[b] Max. number of attempts per studied and unstudied item was 3

Table 5 Multivariate analysis of variance for the number of correct items and the number of attempts per item at mid-test: less thematically relevant audio (LA) versus more thematically relevant audio (MA)

Source	Dependent variable	*SS*	*df*	*MS*	*F*	*p*	η_p^2
Thematically relevant audio	Studied						
	Number of correct items	0.11	1	0.11	0.42	.518	.00
	Number of attempts per item	1.19	1	1.19	4.79	.030	.03
	Unstudied						
	Number of correct items	0.38	1	0.38	0.09	.764	.00
	Number of attempts per item	0.36	1	0.36	1.76	.188	.01

Table 6 Means and standard deviations for the number of correct items and the number of attempts per item at mid-test: less thematically relevant movements (LM) versus more thematically relevant movements (MM)

	n	Studied		Unstudied		Total	
		M	*SD*	*M*	*SD*	*M*	*SD*
Number of correct items[a]							
LM	66	2.79	0.60	6.06	2.21	8.85	2.46
MM	74	2.85	0.39	7.27	1.87	10.12	1.99
Number of attempts per item[b]							
LM	66	1.45	0.59	2.05	0.46	1.90	0.40
MM	74	1.36	0.41	1.81	0.45	1.70	0.36

[a] Max. number of correct studied items is 3; max. number of correct unstudied items is 9

[b] Max. number of attempts per studied and unstudied item was 3

Participants experiencing the more thematically relevant audio answered significantly more correct studied items ($M = 9.65$, $SD = 1.24$) compared to participants experiencing the less thematically relevant audio ($M = 9.12$, $SD = 1.53$). For the unstudied items, the

Table 7 Multivariate analysis of variance for the number of correct items and the number of attempts per item at mid-test: less thematically relevant movements (LM) versus more thematically relevant movements (MM)

Source	Dependent variable	*SS*	*df*	*MS*	*F*	*p*	η_p^2
Thematically relevant movements	Studied						
	Number of correct items	0.13	1	0.13	0.52	.474	.00
	Number of attempts per item	0.41	1	0.41	1.65	.201	.01
	Unstudied						
	Number of correct items	51.33	1	51.33	12.17	.001	.08
	Number of attempts per item	1.93	1	1.93	9.27	.003	.06

audio-related perceptual factor was not a significant predictor. In terms of the number of attempts per studied item, the audio-related perceptual factor was a marginally significant predictor: F (1, 136) = 3.74, $p = .055$, $\eta_p^2 = .03$. More specifically, participants experiencing the more thematically relevant audio used significantly fewer attempts per studied item ($M = 1.32$, $SD = 0.30$) compared to participants experiencing the less relevant audio ($M = 1.40$, $SD = 0.34$). The audio-related perceptual factor was not a significant predictor of the mean number of attempts per unstudied item. See Tables 9 and 10 for details.

Kinesthetic-related perceptual factor at post-test

The kinesthetic-related perceptual factor was a significant predictor of the number of correct studied items at post-test: F (1, 136) = 5.05, $p = .026$, $\eta_p^2 = .04$. Participants experiencing the more thematically relevant movements answered significantly more studied items correctly ($M = 9.65$, $SD = 1.24$) compared to participants experiencing the less thematically relevant movements ($M = 9.12$, $SD = 1.53$). Additionally, the kinesthetic-related perceptual factor was found to be a significant predictor of the number of correct unstudied items: F (1, 136) = 3.32, $p = .071$, $\eta_p^2 = .02$. Participants experiencing the more thematically relevant movements answered significantly more unstudied items correctly ($M = 7.41$, $SD = 1.18$) compared to participants using the less thematically relevant movements ($M = 6.95$, $SD = 1.64$). Finally, the kinesthetic-related perceptual enhancement was not a significant predictor of the mean number of attempts per studied item or unstudied item at post-test. See Tables 11 and 12 for details.

Discussion

The purpose of this study was to examine if student understanding of new material could be promoted by manipulating the perceptual factors experienced at the time of learning. It was hypothesized that the thematic relevance of a digital environment's perceptual factors would be a significant contributor to learner understanding. To test this hypothesis, participants with limited prior knowledge of multiplication were introduced to the two and three times tables using a virtual manipulative software. While interacting with the environment, participants encountered varied levels of thematic relevance in the audio and bodily-kinesthetic sensory modalities. The following section discusses the findings and their implications.

Table 8 Means and standard deviations for the number of correct items and the number of attempts per item at post-test: control groups versus experimental groups

	n	Studied				Unstudied			
		M	*SD*	*t*	*p*	*M*	*SD*	*t*	*p*
Number of correct items[a]									
Cont.	33	3.42	2.73	12.21	<.001	2.73	1.92	12.54	<.001
Exp.	140	9.40	1.41			7.19	1.43		
Number of attempts per item[b]									
Cont.	33	2.44	0.48	12.27	<.001	2.43	0.49	11.27	<.001
Exp.	140	1.36	0.32			1.46	0.43		

[a] Max. number of correct studied items is 3; max. number of correct unstudied items is 9

[b] Max. number of attempts per studied and unstudied item was 3

Table 9 Means and standard deviations for the number of correct items and the number of attempts per item at post-test: less thematically relevant audio (LA) versus more thematically relevant audio (MA)

	n	Studied		Unstudied		Total	
		M	*SD*	*M*	*SD*	*M*	*SD*
Number of correct items[a]							
LA	67	9.12	1.53	6.95	1.64	16.08	2.96
MA	73	9.65	1.24	7.41	1.18	17.05	2.18
Number of attempts per item[b]							
LA	67	1.40	0.34	1.50	0.49	1.45	0.36
MA	73	1.32	0.30	1.43	0.38	1.37	0.29

[a] Max. number of correct studied items is 10; max. number of correct unstudied items is 8

[b] Max. number of attempts per studied and unstudied item was 3

Auditory perceptual factor

The first research question asked if changes in the thematic relevance of the audio perceptual factor would impact learner understanding of multiplication. The results suggest this factor did impact participants' understanding of multiplication but not in the manner predicted.

It was hypothesized that more thematically relevant audio, operationalized as verbal voiceovers, would assist participants in understanding multiplication as measured by their ability to answer familiar and novel multiplication items accurately and efficiently. In terms of accuracy, after five 20-minute sessions, or approximately 100 min of exposure to the audio perceptual factor, thematic relevance did not predict the number of studied or unstudied items answered correctly. However, after ten 20-minute sessions, or approximately 200 min of exposure, the audio perceptual factor did have a measureable impact. Specifically, participants experiencing the more thematically relevant audio answered significantly more studied items correctly ($M = 9.65$, $SD = 1.24$) compared to participants

Table 10 Multivariate analysis of variance for the number of correct items and the number of attempts per item at post-test: less thematically relevant audio (LA) versus more thematically relevant audio (MA)

Source	Dependent variable	*SS*	*df*	*MS*	*F*	*p*	η_p^2
Thematically relevant audio	Studied						
	Number of correct items	7.96	1	7.96	4.20	.042	.03
	Number of attempts per item	0.37	1	0.37	3.74	.055	.03
	Unstudied						
	Number of correct items	0.51	1	0.51	0.25	.617	.00
	Number of attempts per item	0.00	1	0.00	0.00	.963	.00

Table 11 Means and standard deviations for the number of correct items and the number of attempts per item at post-test: less thematically relevant movement (LM) versus more thematically relevant movement (MM)

	n	Studied		Unstudied		Total	
		M	*SD*	*M*	*SD*	*M*	*SD*
Number of correct items[a]							
LA	66	9.12	1.53	6.95	1.64	16.08	2.96
MA	74	9.65	1.24	7.41	1.18	17.05	2.18
Number of attempts per item[b]							
LA	66	1.40	0.34	1.50	0.49	1.45	0.36
MA	74	1.32	0.30	1.43	0.38	1.37	0.29

[a] Max. number of correct studied items is 10; max. number of correct unstudied items is 8

[b] Max. number of attempts per studied and unstudied item was 3

experiencing the less thematically relevant audio ($M = 9.12$, $SD = 1.53$). In contrast, there was no statistical difference in the number of unstudied items answered correctly. In terms of efficiency, it was predicted that the more thematically relevant audio would benefit learners. However, consistent with the accuracy results, the more thematically relevant audio influenced the number of attempts per studied items but not the unstudied items. This was true for the mid-test and the post-test.

What do these results tell us about the role of thematic relevance experienced via the audio sensory modality in promoting understanding of new material? To begin with, the results support the idea that changes in the audio sensory experience can influence learners' ability to process new material. In this case, the more thematically relevant audio assisted participants in recalling the answers to studied multiplication items. Evidence supporting this interpretation comes from the fact that participants who experienced the more relevant audio were statistically more efficient when answering previously studied multiplication questions from the two and three times tables. In addition, and perhaps more convincingly, these same participants answered significantly more studied items correctly on the post-test. Together, these results demonstrate the ability of a thematically relevant perceptual factor, experienced in the audio sensory modality, to promote partial understanding of new material.

Table 12 Multivariate analysis of variance for the number of correct items and the number of attempts per item at post-test: less thematically relevant movement (LM) versus more thematically relevant movement (MM)

Source	Dependent variable	*SS*	*df*	*MS*	*F*	*p*	η_p^2
Thematically relevant movements	Studied						
	Number of correct items	9.57	1	9.57	5.05	.026	.04
	Number of attempts per item	0.28	1	0.28	2.83	.095	.02
	Unstudied						
	Number of correct items	6.68	1	6.68	3.32	.071	.02
	Number of attempts per item	0.20	1	0.20	1.06	.306	.01

One explanation for these findings is that the more thematically relevant audio helped participants memorize the math facts they encountered during the practice sessions. Thus, when it came time to recall the studied math facts for the mid-test and post-test, participants were more accurate and efficient. These findings are consistent with previous research related to the modality effect, which proposes learning can be enhanced if "textual information is presented in an auditory format" (Ginns 2005, pp. 313–314).

To our surprise, however, this effect was not detectable on the mid-test. Rather it appeared only in the post-test results, which assessed participant knowledge after about 200 min of exposure to the perceptual factor. This suggests there is a temporal aspect to information experienced in the audio modality—perhaps multiple exposures to the same information are necessary before any cognitive correspondence can be formed between the audio sensory modality and abstract concepts. Other mediating factors might be the quantity of content participants were asked to learn or their low prior knowledge at the start of the intervention. In short, further research is needed to understand why thematic relevance in the audio modality did not have an impact in the first 100 min of exposure.

Another interesting aspect of our findings is the fact that the more thematically relevant audio did not help participants transfer their knowledge to unstudied items from the four and five times tables. This suggests the audio perceptual factor assisted learners with memorizing math facts but did not help them uncover the procedural or conceptual patterns inherent in multiplicative thinking. Again, further research is needed to determine if audio perceptual factors can be designed in ways that assist learners beyond mere memorization of declarative knowledge.

Kinesthetic perceptual factor

The second research question asked if changes in the thematic relevance of a kinesthetic perceptual factor would impact student understanding of multiplication. The results suggest that the thematic relevance of the kinesthetic modality had a positive impact on participants' understanding of the target concept.

It was predicted that the more thematically relevant movements would assist participants in learning multiplication as measured by their ability to answer familiar and novel multiplication items accurately and efficiently. In terms of accuracy, the mid-test results found the thematic relevance of the kinesthetic perceptual factor to predict the number of correct unstudied items but not the number of correct studied items. However, by the post-test, the thematic relevance of the kinesthetic perceptual factor mediated the number of correct answers to studied *and* unstudied multiplication items. In all three instances where there was a significant difference in accuracy, the participants experiencing the more thematically relevant movements outperformed the other participants. In terms of efficiency, the thematic relevance of the kinesthetic factor did not predict the mean number of attempts per studied or unstudied problem, with one exception on the mid-test.

In our interpretation, these findings provide strong evidence that kinesthetic perceptual factors can be leveraged to influence cognitive correspondence and ultimately learning outcomes. The participants in this study practiced the same multiplication problems, in the same order, for the same number of times, but the learners who experienced the more thematically relevant movements were able to solve significantly more studied *and* unstudied multiplication items. In other words, they transferred their understanding of how to solve multiplication items from the two and three times tables to unstudied items from the four and five times tables. This was not the case for participants experiencing the less thematically relevant movements, suggesting they may have experienced less cognitive correspondence as a result of their behavioral interactions.

We hypothesized that the two levels of the kinesthetic perceptual factor would result in qualitatively different physical experiences that would ultimately shape learners' ability to make sense of the target concept. We argued that the touchscreen interface would support more thematically relevant movements because it allowed participants to interact directly with the on-screen objects. Indeed, by placing their fingers directly on the on-screen objects, a casual link between participants' movements and the underlying mathematics may have been more tangible for the young learners. The result was a one-to-one correspondence that may have leveraged the "privileged relationship between fingers and numbers" (Andres et al. 2007, p. 563), increasing opportunity for participants to experience a grounded relationship between their physical actions and the abstract concept of multiplication—a scenario less likely given the concurrent visual-motor and cognitive demands required by the less thematically relevant movements (see Costigan et al. 2012).

Temporal aspect of perceptual factors

Our final research question focused on the temporal aspect of the perceptual factors and their impact. The results reveal that the amount of time learners experienced the perceptual factors did impact their understanding. For the audio perceptual factor, the findings were clear: 100 min of exposure to the more thematically relevant audio was not enough time. However, after 200 min the differences were apparent and statistically significant. This indicates that increased exposure to audio perceptual factors was necessary in order to mediate participant understanding of the target concept. In other words, participants did not use the verbal voiceovers to memorize the math facts in a "one and done" fashion. Rather, it seems they needed repeated exposure in order to benefit from the voiceovers. An experimental design that did not allow for multiple measures over a relatively "extended" period of time might have missed this aspect of the audio perceptual factor. Finally, timing appeared to be an element in the kinesthetic perceptual factor's impact as well. In this case, the distinction between the more and less thematically relevant movements was detectable after 100 min of exposure and these differences continued as evidenced by the post-test results.

Conclusion

Taken together, the work presented here provides evidence that perceptual richness defined as converging sensorimotor input can mediate understanding of new material presented in a digital learning environment. The results show that perceptual factors and their corresponding levels of thematic relevance can mediate participant understanding in different ways and over different time scales. We feel these findings warrant further investigation as digital environments become more capable and more content is made available digitally.

While interpreting this work, it is important to acknowledge some of its limitations. One limitation concerns the fact that our participants represented a narrow band of learners in terms of their prior knowledge; therefore, one must use caution when generalizing to broader groups. By design, participants were selected for their proficiency with addition and minimal knowledge of multiplication, which left them well positioned for an introduction to multiplicative thinking. Of course, participants with more varied backgrounds are likely to produce different results. A second limitation is the lack of a delayed post-test. Future work should examine how the two perceptual factors impact learner understanding after a week or two without the software. A third limitation is the study's reliance on a single researcher-developed data source—the multiplication mid-test and post-test. This limitation reduces the practical implications of our work. To avoid this issue in the future, researchers should examine the relationship between perceptual richness and learning outcomes using multiple standardized assessments.

Despite its limitations, the study contributes to the field's understanding of learning in digital environments. It also raises important questions about how perceptual richness and its constituent perceptual factors are attended to and processed by learners. Today's findings make it clear that more research is needed to better understand the role of the body and the senses in grounding perceptual experience and abstract concepts.

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