Embodied Learning with Physical and Virtual Manipulatives in an Intelligent Tutor for Chemistry

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Abstract. Blended educational technologies can leverage complementary benefits of physical and virtual manipulatives. However, it is not clear how best to combine these manipulatives. Prior research has focused on combining physical and virtual manipulatives by offering them sequentially based on whether they make a specific concept salient. This research has mostly ignored embodied learning mechanisms that can ground students' conceptual understanding in bodily actions. To address this issue, we conducted a lab experiment on chemistry learning with 80 undergraduate students. We compared different ways of sequencing virtual and physical manipulatives in ways that first engaged students in embodied experiences or made the target concepts salient. Results suggest that providing embodied experiences early in the learning sequence enhances conceptual learning. These findings extend extant theory on blending physical and virtual manipulatives and provide practical advice for developers of blended interactive educational technologies.

Keywords: Blended technologies · Physical/virtual manipulatives · Embodiment

1 Introduction

Blended educational technologies that combine physical and virtual experiences are becoming increasingly popular [1, 2]. This has revived a century-old debate about when physical manipulatives enhance learning [3]. For example, chemistry students may interact with physical or virtual manipulatives while learning about atoms (Fig. 1). Physical manipulatives are tangible objects that students construct with their hands (Fig. 1a). Virtual manipulatives are displayed on a screen and are manipulated by mouse, keyboard, or touchscreen (Fig. 1b). The goal of blended technologies is to combine these manipulatives in a way that leverage their complementary benefits [1, 2, 4].

A prevalent way of blending physical and virtual manipulatives is to provide them sequentially [5–7]. However, prior studies yield conflicting results as to how physical or virtual manipulatives should be sequenced (e.g., [5, 7]). To resolve these conflicts, a dominant blending framework [1, 4] proposes that students should work with the manipulative that makes task-relevant concepts salient by drawing students' attention to

M. M. Rodrigo et al. (Eds.): AIED 2022, LNCS 13355, pp. 103–114, 2022.
https://doi.org/10.1007/978-3-031-11644-5_9

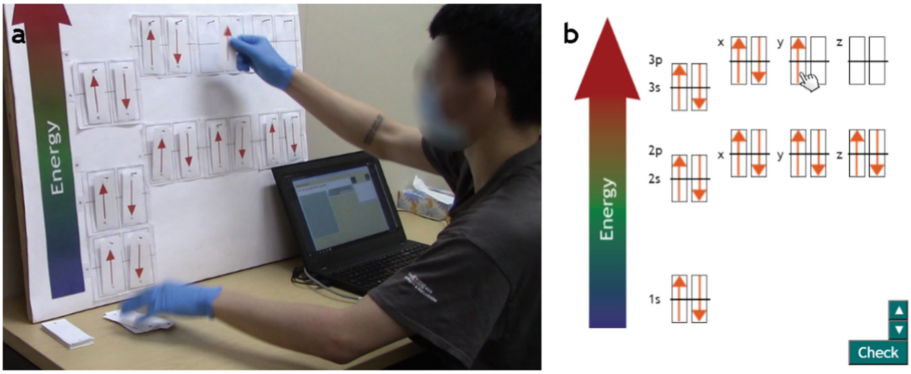

Fig. 1. Physical (a) and virtual (b) manipulatives showing an atomic orbital energy diagram.

the concepts. When students switch to a different task, they may switch to a different manipulative that better aligns with the concepts relevant to the new task.

A limitation of this blending framework is that it solely focuses on conceptual learning processes. Yet, embodied processes also affect students' learning with physical and virtual manipulatives [8]. Most prior research on blended educational technologies has focused on conceptual processes (e.g., [9–11]) while disregarding embodied processes [8]. The lack of research that integrates both processes is problematic. First, focusing on only a subset of relevant processes may lead to confounded experiments, which may contribute to conflicting results from prior studies. Second, research needs to compare the relative strength of these processes to determine which process accounts for the observed sequence effects. Without such knowledge, we cannot make recommendations for when students should receive a physical or virtual manipulative. Further, such knowledge will determine which process adaptive blended technologies should trace to assign physical or virtual manipulatives based on an individual's learning progress.

To achieve these goals, we present an experiment that systematically varied design features of manipulatives that affect conceptual and embodied processes. We tested sequences of physical and virtual manipulatives within an intelligent tutoring system.

2 Theoretical Background

2.1 Learning Processes Affected by Physical and Virtual Manipulatives

A recent review [8] showed that prior studies mostly focus on how physical and virtual manipulatives make concepts salient while fewer studies focus on embodied processes.

Conceptual salience describes the capacity of a visual representation to draw students' attention to visual features that depict conceptually relevant information [8]. Concepts may become salient because visual design features of the manipulative draw students' attention to them [12] or because students' interactions with the manipulative draw attention to a specific feature that depicts conceptual information [13].

According to this perspective, whether a physical or virtual manipulative is more effective depends on which makes a concept more salient [1]. For instance, physical manipulatives are more effective if they allow students to experience spatial concepts [14, 15] or offer concrete experiences relevant to the target concept [16]. As mentioned, the dominant blending framework [1] recommends to match physical and virtual manipulatives to learning tasks based on whether they make the target concept conceptually salient. Indeed, this way of blending physical and virtual manipulatives leads to higher learning gains than working with only physical or only virtual manipulatives [4].

In sum, the dominant view is that the type of manipulative that makes the target concept salient should be most effective.

Embodied theory assumes that cognition evolved for humans to mentally simulate effects of their actions [17, 18]. Hence, abstract thinking builds on mental simulations of body actions. For example, understanding growth functions builds on experiences of growth and increase in the real world. We distinguish two tenets of this theory [8, 13].

Explicit embodiment emphasizes the importance of explaining relationships between kinesthetic experiences and concepts [8]. Physical manipulatives may allow students to experience a target concept through the sense of touch and motion [19]. Students can explicitly connect these embodied experiences to the concept. For example, suppose manipulating a physical manipulative involves lifting an object. Prompting students to explain how the physical effort associated with this action relates to concepts of kinetic and potential energy can help students understand these concepts. Explicit embodied experiences can perceptually ground students' understanding of abstract concepts [20]; that is, students' gradual understanding of abstract concepts based on concrete experiences becomes increasingly stylized [21, 22]. Indeed, perceptual grounding enhances learning outcomes [23]. Thus, explicit embodiment suggests that physical manipulatives are advantageous if they allow students to explain connections between the target concepts and experiences of touch and movement.

Implicit embodiment emphasizes the importance of body movements without requiring that students are aware of the connections between the movement and the concept [8]. Building on the idea that thought is a mental simulation of action [24, 25], even abstract concepts (e.g., justice) are based on real-world experiences (e.g., balance), often without our awareness of this connection [26]. This implies that instruction should invoke embodied schemas relevant to the target concept [27]. Embodied schemas can be invoked by metaphors, body movements, or gesture [28, 29]. Students' learning of a concept is enhanced if they receive instruction on the concept while moving their body in ways that are synergistic to the associated embodied schema, even if they are not aware that their movement related to the concept [20, 30]. For example, moving one's hand upwards may activate an embodied schema related to increase, which can help students learn concepts related to growth.

Implicit embodiment is not only afforded by physical but also by virtual manipulatives. When virtual manipulatives are manipulated in ways that invoke synergistic embodied metaphors, students learn the target concept better than when manipulating the same manipulative with less synergistic movements [31]. Because physical and virtual manipulatives often engage students in different movements, implicit embodiment has implications for which type of manipulative is most effective. For example, to manipulate a physical manipulative, a student may move their hand vertically, which implicitly invokes embodied schemas related to growth and increase. In contrast, a virtual manipulative may require a sideways movement that invokes embodied schemas of balance and equality. Depending on which embodied schema matches the target concept, one or the other type of manipulative may be more effective [8].

In sum, implicit embodiment suggests that manipulatives are more effective if they invoke embodied schemas that match the target concept without requiring awareness of the match.

2.2 Blending Physical Versus Virtual Manipulatives

There is no empirical basis for the superiority of physical or virtual manipulatives [8]. Many studies showed that physical and virtual manipulatives complement each other by making different concepts salient [1, 6, 9]. Hence, research investigated how to blend these manipulatives by sequencing them in a way that best leverages their strengths [7–13]. This yielded the dominant blending framework [1, 4], which suggests that manipulatives should be chosen based on their ability to make concepts salient.

Yet, the dominant blending framework is limited because it is based on studies that focused only on conceptual salience of the target concepts and thus conflated ways that the manipulatives affected embodied processes [8]. Our prior work [32] started addressing this limitation. We systematically varied whether physical and virtual manipulatives implicitly induced embodied schemas that were synergistic to the target concepts, offered explicit embodied experiences of the concepts, and provided visual cues that made the concepts salient. We found that implicit embodiment yielded higher learning gains on a reproduction test. However, physical manipulatives that offered explicit embodied experiences yielded higher gains on a transfer test. If explicit embodiment was not available for a given concept, manipulatives (physical or virtual) that made the concept salient yielded higher transfer gains. We interpreted the findings based on the complexity of the learning outcome [13, 33]: Implicit embodiment enhanced simple learning outcomes (i.e., reproduction). In contrast, explicit embodiment and conceptual salience (both explicit processes) enhanced complex outcomes (i.e., transfer). We consider explicit embodiment more complex than conceptual salience because it allows students to make more connections between the manipulative and the concept (embodied plus visual experience vs visual experience only). This explains the benefit of explicit embodiment compared to the effects of conceptual salience.

3 Research Questions and Hypotheses

Our prior study suggests that effects of physical and virtual manipulatives affect learning outcomes not only via conceptual processes but also via embodied processes. Further, the different processes affect different learning outcomes. This raises the question of how manipulatives should be sequenced to best leverage implicit and explicit embodiment as well as conceptual salience. Our prior study suggests two hypotheses:

On the one hand, instruction often progresses from simple to complex. This yields the *simple-first (SF) hypothesis:* Students should first work with manipulatives that engage simple learning processes by implicitly inducing embodied schemas relevant to the concept. Then, they should work with manipulatives that engage complex processes by offering explicit embodied experiences of the concept. If explicit embodiment is unavailable, the manipulative should make the concept salient. This should enhance students' ability to construct correct manipulatives ($H_{SF\text{-}1}$) and learning gains ($H_{SF\text{-}2}$).

On the other hand, students may need to acquire deep understanding of a complex concept before they should practice simple recall. This yields the *complex-first (CF) hypothesis:* Students should first work with manipulatives that engage complex processes by offering explicit embodied experiences of the target concept (or, if not available, make the concept salient). Then, they should work with manipulatives that engage simple processes by implicitly inducing embodied schemas. This should enhance students' ability to construct correct manipulatives ($H_{CF\text{-}1}$) and learning gains ($H_{CF\text{-}2}$).

The goal of the present study is to systematically test these hypotheses. To this end, we conducted an experiment on students' use of manipulatives in a chemistry lesson.

4 Methods

4.1 Participants

Eighty undergraduate students were recruited from our institution via flyers and emails. Screening questions ensured they were naïve to the content and the manipulatives.

4.2 Experimental Design

In line with our prior study [32], we created four types of energy diagram manipulatives. For two concepts (A and B), they offered either conceptual or implicit-embodied experiences: two physical manipulatives (physical$_{conceptual}$, P_C; and physical$_{implicit\text{-}embodied}$ P_{IE}), and two virtual manipulatives (V_C; V_{IE}). As detailed below and shown in Table 1, P_C and P_{IE} offered explicit-embodied experiences for concept A but not for concept B.

Table 1. Overview of physical (P_C/P_{IE}) vs virtual (V_C/V_{IE}) manipulatives and target concepts.

Process		**Concept A**				**Concept B**			
Complexity	*Type of experience*	P_C	P_{IE}	V_C	V_{IE}	P_C	P_{IE}	V_C	V_{IE}
Complex	Explicit-embodied	✓	✓	-	-	-	-	-	-
↕	Conceptual	✓	-	✓	-	✓	-	✓	-
Simple	Implicit-embodied	-	✓	-	✓	-	✓	-	✓

Concept A: Electrons Randomly Fill Equal-Energy Orbitals.
Atomic properties are determined by the location of their electrons in subatomic regions called orbitals. Energy diagrams show the location of electrons and the relative energies of orbitals (Fig. 1). Electrons fill lower energy orbitals before higher energy orbitals.

Because equal-energy orbitals are equally likely to be filled, many atoms have alternative energy diagrams. A common misconception is that electrons fill equal-energy orbitals from left to right, rather than randomly. Target concept A was for students to learn that electrons randomly fill equal-energy orbitals.

To construct $\mathbf{P_C}$, students moved cards that showed electrons from the bottom up to put them in orbitals (Fig. 1A). P_C makes the *concept salient* because planning the motor action involved in the vertical action requires attention to the height of the orbital when students put a card in an orbital. However, this vertical action implicitly induces a *conflicting embodied schema* because it aligns with a metaphor of increase [26] that conflicts with the concept of equality.

To construct $\mathbf{P_{IE}}$, students held the cards next to the orbitals and moved their hands horizontally to put them in orbitals. The horizontal action makes the *concept less salient* because it does not require paying attention to the height of the orbitals. However, this horizontal action implicitly induces *beneficial embodied schemas* for the concept because horizontal actions induce a metaphor of equality [26].

Both $\mathbf{P_C}$ and $\mathbf{P_{IE}}$ offer *explicit embodied experiences* of concept A because students can physically experience the height of the orbital.

To construct $\mathbf{V_C}$, students had to click a button at the bottom of the interface each time before moving the mouse up to put arrows in orbitals. This vertical action makes the *concept more salient* but implicitly induces a *conflicting embodied schema.*

To construct $\mathbf{V_{IE}}$, students had to move the mouse horizontally to click in equal-energy orbitals (Fig. 1B). V_{IE} makes the *concept less salient* but implicitly induces a *beneficial embodied schema.*

$\mathbf{V_C}$ and $\mathbf{V_{IE}}$ offer *no explicit embodied experience* of concept A.

Concept B: Up and Down Spins Have Equal Energy. Electrons in the same orbital have opposite spins (shown by up and down arrows; Fig. 1). Up and down spins are equally likely. A common misconception is that the first electron in an orbital always has an up spin. Hence, target concept B was for students to learn that both spins are equally likely.

For $\mathbf{P_C}$, the card stack was sorted so that all cards had an up arrow. This makes the concept *more salient* because students had to purposefully flip the arrows to show that the spins are equally likely, which requires explicit attention. Yet, this implicitly induces a *conflicting embodied schema* because it takes two actions to show a down spin (i.e., more effort) and only one action to show an up spin (i.e., less effort).

For $\mathbf{P_{IE}}$, the card stack was not sorted, so that up and down arrows were random. This makes the *concept less salient* because the spin is already random and does not require attention to a related action. Yet, this implicitly induces a *beneficial embodied schema* because it takes the same number of actions and hence the same amount of effort to show up or down spin.

In $\mathbf{V_C}$, students clicked to add arrows. The first click added an up arrow, the second click flipped it to a down arrow. V_C makes the *concept more salient* because students had to purposefully flip the arrows. Yet, this implicitly induces a *suboptimal embodied schema* because it took two clicks to show a down spin (more effort) but only one click (less effort) to show an up spin. V_C offers *no explicit embodied experience* of spin.

In $\mathbf{V_{IE}}$, the first click created an arrow with random spin and the second click flipped it. This makes the *concept less salient* but induces a *beneficial embodied schema*. V_{IE} offers *no explicit embodied experience* of spin.

$\mathbf{P_C}$, $\mathbf{P_{IE}}$, $\mathbf{V_C}$, and $\mathbf{V_{IE}}$ offer *no explicit embodied experience* of spin.

Experimental Design: Sequences of Manipulatives. The experiment involved two sessions. Session 1 covered concept A and session 2 covered concept B. The experiment varied the sequence of mode (P-V vs V-P) and of design (IE-C vs C-IE).

Specifically, students were randomly assigned to one of four conditions for session 1: P_C-V_{IE}, P_{IE}-V_C, V_C-P_{IE}, or V_{IE}-P_C. For session 2, students were assigned to a condition that offered manipulatives they had not encountered in session 1. For example, if students received P_C-V_{IE} in session 1, they received either P_{IE}-V_C or V_C-P_{IE} in session 2. This ensured that all students received each manipulative. Further, this design allowed us to test the two competing hypotheses in the following manner. The *simple-first hypothesis* predicts an advantage for V_{IE}-P_C and P_{IE}-V_C over P_C-V_{IE} and V_C-P_{IE} because these sequences engage students in simple learning processes first (i.e., V_{IE} and P_{IE}), and then engage students in complex learning processes (i.e., P_C and V_C). For concept A, this advantage should be particularly pronounced for V_{IE}-P_C because P_C offers explicit embodied experiences in addition to making the concept salient.

By contrast, the *complex-first hypothesis* predicts an advantage for P_C-V_{IE} and V_C-P_{IE} over V_{IE}-P_C and P_{IE}-V_C because these sequences engage students in complex learning processes first (i.e., P_C and V_C), and then in simple learning processes (i.e., V_{IE} and P_{IE}). For concept A, this advantage should be particularly pronounced for P_C-V_{IE} because P_C offers explicit embodied experiences in addition to making the concept salient.

4.3 Materials

Intelligent Tutoring System: Chem Tutor. All students worked with Chem Tutor, an intelligent tutoring system for undergraduate chemistry [34, 35]. Chem Tutor engages students in iterative representation-reflection practices by asking them to construct manipulatives and reflect on how the manipulative shows the target concepts.

Students worked through a sequence of eight problems focused on concept A and five problems focused on concept B. Each problem asked students to construct an energy diagram. Physical manipulatives (P_C/P_{IE}) were placed next to the computer (Fig. 1a). Virtual manipulatives (V_C/V_{IE}) were embedded in Chem Tutor. Chem Tutor provided feedback and on-demand hints on all problem-solving steps, including the manipulatives. For physical manipulatives, the experimenter provided scripted feedback and hints that matched those provided by Chem Tutor.

Measures. We assessed students' *conceptual knowledge* with a pretest, immediate posttest, and delayed posttest for each concept. For each concept, the tests included a reproduction scale (i.e., assessing recall of information about the concept) and a transfer scale (i.e., assessing the ability to apply the information to novel problems).

Further, as instruction was self-paced, we measured *time on task* for each concept.

Finally, we computed *errors* as the proportion of mistakes per step in manipulating V_C and V_{IE} with log data and in manipulating P_C and P_{IE} based on video recordings.

4.4 Procedure

The experiment involved three sessions in a research lab. In session 1, students completed the concept A pretest, Chem Tutor problems on concept A, and took the concept A posttest. In session 2 (2–5 days later), students completed the concept A delayed posttest, the concept B pretest, Chem Tutor problems on concept B, and the concept B posttest. In session 3 (2–5 days later), students took the concept B delayed posttest.

5 Results

5.1 Prior Checks

One student was excluded for scoring 2 standard deviations above the median. Repeated measures ANOVAs with pretest, immediate, and delayed posttest as dependent measures showed learning gains for all concepts and scales (*p*s < .01) with effect sizes ranging from p. $\eta^2 = .568$ to p. $\eta^2 = .876$. For concept A, we found no significant condition effects on pretest measures and time on task (*p*s > .10). For concept B, there were no significant differences on the pretests (*p*s > .10), but a significant effect on time on task ($p = .01$). Post-hoc comparisons showed that students in the P_C-V_{IE} condition took significantly longer than students in the V_C-P_{IE} condition ($p = .008$). Time on task correlated with posttests ($r = -.244$ to $-.558$). Thus, we use it as covariate in our analyses.

5.2 Effects on Error Rates During Interactions with Manipulatives

We used a repeated ANCOVA with mode-sequence (P-V vs V-P) and design-sequence (IE-C vs C-IE) as independent factors, mode-type (P vs V) as repeated measures, pretest and time on task as covariates, and errors as dependent measure. For *concept A*, the effect of mode-sequence was significant, $F(1, 72) = 5.309$, $p = .024$, p. $\eta^2 = .069$. Students who received physical manipulatives first made fewer errors, which partially supports $H_{CF\text{-}1}$. For *concept B*, the effect of design-sequence was significant, $F(1, 72) = 6.664$, $p = .012$, p. $\eta^2 = .085$. Students who received implicit-embodied manipulatives first made fewer errors. This finding supports $H_{SF\text{-}1}$. Figure 2a-b illustrate these results.

5.3 Effects on Learning Outcomes

We used a repeated ANCOVA with mode-sequence (P-V vs V-P) and design-sequence (IE-C vs C-IE) as independent factors, test-time (immediate, delayed posttest) and scale (reproduction, transfer) as repeated factors, pretest and time on task as covariates, and test scores as dependent measures. For *concept A*, there were no main effects of mode-sequence and design-sequence (*p*s > .10), but mode-sequence interacted with test-scale, $F(1, 72) = 9.644$, $p = .003$, p. $\eta^2 = .045$. Pairwise comparisons showed that the P-V sequence yielded better transfer, $F(1, 72) = 6.568$, $p = .012$, p. $\eta^2 = .084$, but did not affect reproduction ($F < 1$). This effect held for P_C-V_{IE} and P_{IE}-V_C. This finding partially supports $H_{CF\text{-}2}$. For *concept B*, there were no effects of mode-sequence or design-sequence (Fs < 1), thus supporting neither $H_{SF\text{-}2}$ nor $H_{CF\text{-}2}$. Figure 2c illustrates the results.

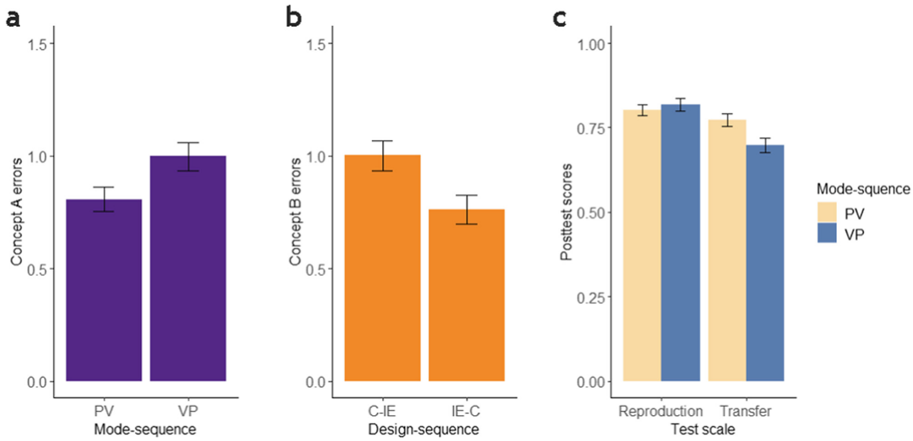

Fig. 2. (a) Effect of mode-sequence on concept A errors; (b) effect of design-sequence on concept B errors; (c) effects of mode-sequence on reproduction and transfer posttests. All bars show estimated marginal means. Error bars show standard errors of the mean.

6 Discussion and Conclusion

Prior research recommends blending physical and virtual manipulatives by sequencing them in a way that makes the target concepts salient. However, a mostly separate line of research shows that explicit and implicit types of embodied processes also affect learning with manipulatives. A severe limitation of prior research is that it had not investigated all three types of processes together. Our prior research had contrasted effects of conceptual, explicit-embodied, and implicit-embodied processes on learning with manipulatives. Results had indicated that these processes differently affect learning outcomes of varying complexity. This gave rise to two competing hypotheses about sequencing physical and virtual manipulatives either so that they engage students in simple learning processes first (i.e., via implicit-embodiment) or so that they engage students in complex learning processes first (i.e., preferably via explicit-embodiment or else via conceptual salience). While the results of the present experiment seem to be complex, two relatively simple patterns emerge. First, explicit embodiment has a strong effect on both errors and learning gains. Second, whether in the form of explicit or implicit embodiment, some type of embodied experience at the beginning of the learning sequence is advantageous. In the following, we discuss each pattern in turn.

First, the finding that the P-V sequence yielded fewer manipulative errors and higher transfer gains for concept A than the V-P sequence partially supports the complex-first hypothesis. Recall that this hypothesis had also predicted an advantage of sequences that start with conceptual salience (i.e., in addition to a main effect of P-V > V-P, an advantage of P_C-V_{IE} > P_{IE}-V_C). Yet, our results suggest that starting with physical manipulatives that offer explicit embodied experiences of the target concept is sufficient. Engaging students in additional complex processes with the concept early in the sequence is not necessary. Further, in line with our prior research, engaging students in complex processes first affects transfer rather than reproduction, suggesting that complex processes align with complex learning goals.

Second, the finding that the IE-C sequence yielded fewer manipulative errors for concept B partially supports the simple-first hypothesis. Recall that the physical manipulatives offered no explicit embodied experiences for concept B. A sequence that first engaged students in complex learning processes via conceptual salience did not offer an advantage compared to implicit embodied experiences related to the concept. Thus, our result indicates that in the absence of explicit embodied experiences, there is some advantage of offering implicit embodied experiences at the beginning of a learning sequence. Given that we contrasted this to a sequence that starts by making the concept salient, our result shows that the benefit of initial implicit embodiment is stronger than a potential benefit of starting with conceptual salience. However, the effect only bears out with respect to reducing students' errors on the manipulative, but not on learning outcomes. It is possible that potential benefits of conceptual salience counteracted any potential advantage of offering implicit embodied experiences first.

Our findings expand research on blending physical and virtual manipulatives in at least two ways. First, our research is the first to consider conceptual salience as well as explicit and implicit embodied experiences, yielding a systematic comparison of sequences. Moreover, no prior research has compared explicit and implicit embodied processes, even though they appear to yield dramatically different outcomes. Second, our findings suggest that blending should not be done purely based on conceptual salience. Wherever possible, manipulatives should first offer explicit embodied experiences of target concepts. Otherwise, implicit embodied experiences can offer some advantages. Consequently, adaptive blended learning technologies should not only trace students' conceptual learning but should also trace their embodied engagements by assessing movement and touch.

Our findings should be interpreted in light of several limitations. First, we focused on one combination of concepts and manipulatives. Other manipulatives lend themselves to studying different combinations of conceptual and embodied designs. For example, we did not include a manipulative that offered implicit embodied experiences while also making the target concept salient. Future research should examine whether it is possible to combine benefits of implicit embodiment and conceptual salience, especially when explicit embodiment is not available. Second, our experiment was conducted in a research lab and should be replicated in a realistic educational context. Third, while long for a lab experiment, our intervention was relatively short for realistic instruction. Future research should examine sequence effects over longer periods.

In conclusion, blended educational technologies offer novel opportunities for combining physical and virtual experiences. The dominant framework that guides extant integrations of physical and virtual manipulatives focuses on conceptual salience while disregarding emerging findings about the importance of embodied engagement. Our research systematically juxtaposed conceptual salience with two types of embodied engagements. Our findings show that explicit embodied engagements early in a learning sequence can significantly enhance students' learning with manipulatives.

Acknowledgements. This work was supported by NSF IIS 1651781.

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