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Investigating embodied mathematical reasoning in a touch-based interactive vector system through motor interference

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Abstract: Embodied cognition suggests that mathematical reasoning can be constituted by sensorimotor engagement rather than occurring independently of the body. We examined whether directed gestures in a tablet-based learning tool, Touchy-Feely Vectors (TFV), become integral to students' vector reasoning. Sixteen ninth-grade students were randomly assigned to TFV or paper-and-pencil instruction and later completed two interference experiments. In Experiment 1, students solved vector problems with and without finger weights to test whether motor disruption impaired performance. Finger weights reduced overall accuracy ($p = .055$), but the effect was comparable across groups. In Experiment 2, students solved vector problems following gesture-video primes that were either compatible or incompatible with the correct answer. Response times showed only a marginal compatibility × group interaction ($p = .054$), with no main effects. Unexpectedly, TFV students underperformed relative to controls, likely due to reduced instructional time and logistical constraints. Together, the findings suggest boundary conditions for embodiment effects: active motor interference modestly affected reasoning, whereas passive gesture priming did not. Broadly, this work highlights how motor-interference and compatibility paradigms could be leveraged in mathematics and physics education research as scalable ways to assess embodiment, framing instructional designs along a continuum rather than as binary categories.

Keywords: Embodied cognition, touchy-feely vectors, motor interference, gesture and learning

1. Introduction

Embodied cognition posits that thinking and learning are not separable from the sensorimotor systems of the body; physical movement and gesture can fundamentally shape and enhance cognitive processes, even in abstract domains such as mathematics (Abrahamson & Lindgren, 2022). Experimental work supports this claim. For example, children taught mathematical equivalence who were instructed to produce hand gestures while explaining their reasoning showed significantly better long-term retention than peers who relied only on speech (Cook et al., 2008). Follow-up research further demonstrated that producing correct gestures during instruction not only improved post-test performance but also led children to incorporate gesture-based strategies into their spoken explanations, suggesting that gesturing can generate new conceptual insights (Goldin-Meadow et al., 2009). However, most empirical studies pit an embodied condition against a more disembodied or traditional condition (e.g., gesture vs. no gesture, physical manipulatives vs. abstract symbols, body-based activity vs. lecture). Few studies have directly compared different types of embodied learning approaches against each other.

In parallel, researchers have developed embodied learning environments that deliberately integrate bodily action into mathematical activity, e.g., the Mathematics Imagery Trainer (Howison et al., 2011), Touchy-Pinchy Integers (Elangaivendan et al., 2023), and Touchy-Feely Vectors (Karnam et al., 2021), all of which embed bodily action directly into the representational system. Touchy-Feely Vectors (TFV), which is the focus of the present study, is a tablet-based learning tool for the vector concept where students can perform hand-driven manipulation of on-screen arrows, such as dragging, rotating, and composing vectors with fingers rather than copying static textbook figures. Each vector operation is enacted through a prescribed gesture, embedding body movement into the representational system itself. Across two design iterations in Indian high-school classrooms (N = 266), TFV outperformed conventional instruction, particularly for average performers (Karnam et al., 2021).

However, much of the current research on embodied learning evaluates embodiment by comparing instructional modes such as “action versus observation” or “gesture versus no gesture,” and then looks for differential outcomes. Such contrasts leave open alternative explanations: benefits in performance may stem from novelty effects, heightened engagement, or increased time-on-task, rather than from embodiment per se. While this approach is reasonable from an educational perspective, it does not fully address the deeper cognitive science question of whether the learned concepts are constituted by sensorimotor involvement. From this perspective, the critical test of embodiment is whether disrupting or inhibiting relevant motor systems reliably diminishes the application or performance of a concept after it is learned. A small but growing set of studies pursue this line of reasoning, using paradigms such as motor interference (occupying or constraining the hands) (Brooks et al., 2018; Michaux et al., 2013; Nathan & Martinez, 2015) or compatibility manipulations, (congruent vs. incongruent gestures) (Cheng et al., 2015; Wu et al., 2024; Yee et al., 2013), to probe whether learned concepts can still be enacted under conditions of motor disruption. Such experimental techniques are crucial for education research as well because they provide a principled way to distinguish between movements that are merely engaging and those that are integral to learning. In the language of task integration (Skulmowski & Rey, 2018), this means asking whether bodily activity is meaningfully tied to the problem-solving process or only incidental to it.

In higher mathematics, too, gesture research has shown that spontaneous hand movements correlate with conceptual insight and proof quality (Nathan & Walkington, 2017). However, whether such movements are cognitively constitutive (i.e., ‘bring into being’ new knowledge/thinking) or merely a byproduct of valid mathematical reasoning remains debated. A large inhibition study by Walkington et al. (Walkington et al., 2018) with U.S. undergraduates (N = 107) found that restraining students’ hands with oven mitts had no reliable effect on geometric proof performance, supporting the byproduct account. Importantly, that study did not test settings where the gesture is explicitly taught as part of the concept. TFV provides exactly such directed gestures; therefore, if motor interference selectively impairs TFV-trained students on vector problems, it would demonstrate that embodied actions have become an integral part of their understanding of vector concepts. Demonstrating such a causal link would strengthen embodiment theories of mathematical cognition and inform instructional design. Conversely, finding null effects would caution designers against relying on gesture-heavy interfaces alone. Either outcome delivers valuable insights for technology-enhanced STEM pedagogy.

2. Methodology

Seventeen ninth-grade students were recruited two weeks before the study by sending information sheets home and collecting parental consent and student assent. They were then randomly placed into a Touchy-Feely Vectors (TFV) group (8 students) or a paper-and-pencil control group (9 students). Both groups received six instructional sessions during their regular physics class, over Weeks 1–2. TFV students worked on tablets with prescribed multi-touch gestures for each vector operation. In the control group, the teacher used a geometric construction method with a scale and protractor. This meant that both groups received gesture-rich training, though via different modalities. Also, each instructional session was scheduled for 50 minutes. However, due to the need to relocate to the computer lab and distribute tablets, TFV students received approximately 35 minutes of active instruction per session, whereas the control group received the full session length in their regular classroom. One of the subjects in the non-TFV group missed 4 out of six classes and hence was excluded from the study. He went through the same final tests as his peers so as to not feel excluded, but his data was not included in the final analysis. This left us with a total of 16 subjects, 8 in each group.

2.1 Experiment 1: Finger Weights

Experiment 1 probed whether bodily state influences vector reasoning, using a 2 × 2 mixed-factorial design. Each student sat in a single session and answered the same multiple-choice vector items in two counter-balanced blocks: once while wearing 170 g finger weights and once without them. The finger weights, designed in-house, consisted of nuts and bolts attached to an elastic band wrapped around the middle phalanx of the fingers (see figure 1a). The weights on the thumb, index, and middle fingers were 36 g each, while those on the remaining fingers were 27 g each. All weights were worn over soft winter gloves (9 g) to ensure comfort and safety, as the metal components could be painful against bare skin. The control group wore identical gloves with elastic bands in the same positions, but without the added weight (see figure 1b). This ensured that any tactile sensation, restriction of movement, or minor discomfort unrelated to the weights was comparable across conditions. This was done so that any performance differences could be attributed specifically to the added weight, rather than to distraction or discomfort from the apparatus itself. Response accuracy, response time, and video-recorded spontaneous gestures were collected, followed by a brief questionnaire.

Figure 1. Experimental setup for Experiment 1 (Finger Weights). (a) Weighted condition: participants wore gloves with elastic bands fitted with nuts and bolts on the thumb, index, and middle fingers (≈170 g total). (b) Control condition: participants wore identical gloves with elastic bands but without added weights. This ensured that tactile sensation and movement restriction were comparable across groups.

2.2 Experiment 2: Gesture Compatibility

Experiment 2 was conducted two weeks after Experiment 1. It examined, using a priming-based interference paradigm, whether gesture compatibility affects performance, using a 2 × 2 mixed-factorial design. Both groups answered identical vector MCQs, with two choices for every question. Each question was preceded by a (priming) video showing a TFV gesture being performed. Questions were classified into two conditions: (i) compatible, where the gesture in the video corresponded to the correct answer, and (ii) incompatible, where the gesture corresponded to the incorrect answer. Response accuracy and response time were recorded.

3. Results

Analyses were conducted on data from 16 students (8 TFV, 8 control).

3.1 Experiment 1

Accuracy data consisting of 192 trials (16 pupils x 6 test items x 2 blocks) was analysed with a binomial generalised linear mixed-effects model. Fixed effects variables were the instruction group (TFV/ non-TFV), finger-weight condition (weighted/unweighted), their interaction, and the response time (RT). Random effects grouping factors were Participant and Question (test item).

Wearing finger weights reduced the odds of a correct response by about 63% ($p = .055$), suggesting a possible real effect that warrants testing with a larger sample (figure 2). The Group × Weights interaction was non-significant, $\chi^2(1) = 0.31$, $p = .579$, indicating that the accuracy cost of weights was similar for both groups. RT had no detectable effect on accuracy ($p = .228$). Interestingly, TFV-trained participants were overall 87% less likely to answer correctly than controls ($p < .001$).

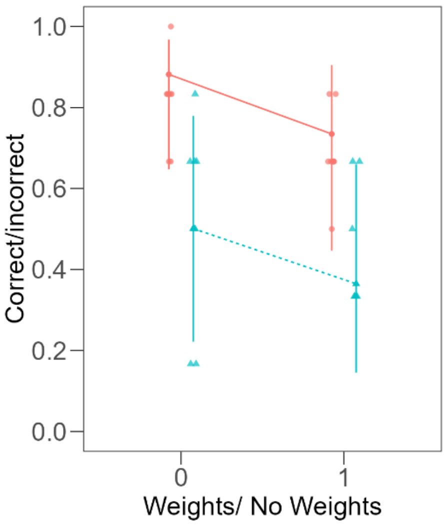

Figure 2. Accuracy in Experiment 1 (Finger Weights). Lines and error bars show model-estimated marginal means with 95% confidence intervals; markers represent individual participants. Red = control (non-TFV), blue = TFV. Both groups showed reduced accuracy under the weights condition, with TFV participants performing worse overall than controls.

3.2 Experiment 2

A linear mixed-effects model was fit to log-transformed RTs with Compatibility (compatible = 1, incompatible = 0), Group (TFV = 1, non-TFV = 0) and their interaction as fixed effects, and random intercepts for participant and question.

The Compatibility × Group interaction showed a small effect (partial $\eta^2 = .007$, Cohen's $f \approx 0.08$) and was marginally significant, $F(1, 522.21) = 3.73$, $p = .054$. Neither the main effect of compatibility, $F(1, 521.33) = 0.05$, $p = .826$, partial $\eta^2 < .001$, nor the main effect of group, $F(1, I13.75) = 0.03$, $p = .867$, partial $\eta^2 = .002$, was significant.

In summary, RTs did not differ significantly by compatibility or instructional group (figure 3). The interaction trend suggests a possible difference in compatibility effects between groups, but the evidence is weak and should be treated as preliminary.

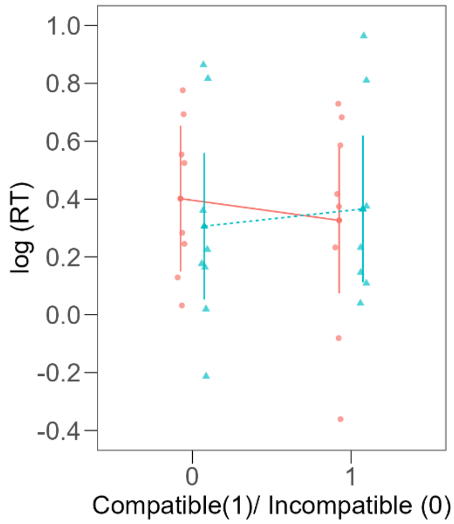

Figure 3. Response times in Experiment 2 (Gesture Compatibility). Lines and error bars show model-estimated marginal means with 95% confidence intervals; markers represent individual participants. Red = control (non-TFV), blue = TFV. No reliable main effect of compatibility was observed, though a weak trend toward a Compatibility × Group interaction. was present.

4. Discussion

The absence of a differential effect of finger weights between groups should be interpreted in light of the instructional context. The control group's instruction involved building vectors with a scale and protractor, a process rich in fine-motor actions and spatial reasoning. Thus, the comparison was not really "embodied vs. non-embodied," but rather "tech-assisted embodied" versus "old-school embodied," which may explain the similar susceptibility to motor interference across groups.

An unexpected result from Experiment 1 was that TFV students scored noticeably lower overall than their paper-and-pencil peers. We believe this too reflects instructional context rather than an inherent limitation of TFV. The TFV group's scheduled 50-minute lessons were reduced to approximately 35 minutes of active instruction due to the need to relocate to the computer lab and distribute tablets. The control group, meanwhile, enjoyed the full period in their own classroom, uninterrupted. This difference in instructional time was fully confounded with group and therefore cannot be statistically separated from group effects. However, a possible reason, which requires further study, would be that TFV students' imagination of vector operations embedded finger movements significantly, and this process was affected by the weight condition.

In Experiment 2, the gesture-compatibility manipulation did not produce a reliable main effect on response times for either group. This suggests that merely viewing a gesture video before the vector operation does not meaningfully influence problem-solving speed in this task. These findings point to a boundary condition for embodiment effects in mathematical cognition: motor interference appears when the body is physically constrained, as in Experiment 1, but not when action cues are delivered passively through visual observation alone. This distinction underscores the likely importance of active motor engagement, rather than passive perception, for gesture-based learning effects to manifest. It remains possible that a concurrent presentation of interfering visual stimuli (gesture videos) would yield a significant interaction; if not, the implication would be that active motor engagement, rather than passive perception, is necessary for gesture-based learning effects to manifest.

Future work could extend these findings in two ways. For Experiment 1, the two instructional groups could then be given distinct representational approaches: the non-TFV group receiving purely algebraic, component-based instruction, and the TFV group receiving geometric instruction with gestures. This might require more advanced students, such as those in Grade 11, who have a solid grounding in algebra and calculus. The subsequent test could include items solvable both algebraically and geometrically, allowing us to examine whether finger-weight interference selectively affects the geometric (TFV) group.

For Experiment 2, passive gesture observation could be replaced with actual gesture performance. After viewing the gesture video, participants could be asked to continuously perform the depicted movement with their dominant hand, till they answer the question with their other hand. This would directly engage the motor system and may produce a clearer compatibility effect.

Overall, the broader aim of this work is to develop quantitative paradigms that can meaningfully measure and compare the "amount of embodiment" afforded by different instructional methods, and their learning effects. Establishing such measures would allow us to move beyond binary labels of “embodied” or “non-embodied”, and instead place instructional designs along a continuum. Once such a reliable metric is in place, future studies could examine how the degree of embodiment relates to other important aspects of learning, including transfer to novel contexts and long-term retention. The present pilot offers two such paradigms, namely, motor interference and compatibility, that could contribute to the measurement framework, though they require further refinement.

Practically, the study has implications for multiple stakeholders. For education researchers, it positions motor interference and compatibility as experimental probes of embodiment that can be applied beyond the vector concept. As empirical findings accumulate across different domains, they can reveal which gestures are constitutive for which concepts. This could allow researchers to move from isolated demonstrations toward general theories of gesture–concept mappings, with the ability to predict in advance which kinds of gestures are likely to be constitutive. For education technology designers, such theories and tools would provide a diagnostic lens: instead of adding gestures or interactivity simply for engagement, they could identify which gestures are decorative versus cognitively essential. A mature toolkit would allow them to test prototypes for embodiment before deployment and substantiate design claims with evidence. Teachers would benefit indirectly, as research and design informed by these methods feed back into the classroom, ensuring that embodied approaches are both theoretically grounded and practically effective.

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