Physical manipulatives provide spatial and arithmetic performance advantages in canonical education activities

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Abstract

Digital devices have become ubiquitous fixtures in classrooms nationwide. Despite this rapid incorporation of tablet computers in educational settings, the costs and benefits of digitization are understudied. Performance differences in reading have been observed across physical and digital modalities. The current study extends these findings to physical and digital versions of spatial tasks. Participants engaged in identical sets of tangrams and demonstrated notable performance differences in both accuracy and response time. Participants subsequently completed a timed arithmetic test, demonstrating an advantage in mathematical problem solving if physical manipulatives, rather than a digital interface, were used in the tangram task. These results suggest that moving toward digitization of spatial tasks may have far-reaching implications that could compromise learning.

Background & Motivation

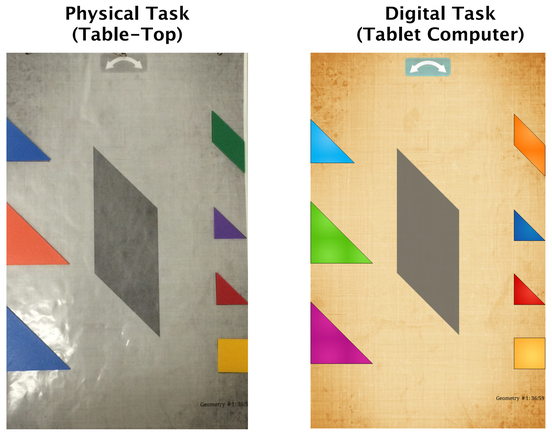
Making the best use of new technologies requires a nuanced understanding of their affordances.

- More than 1/3 of US middle and high school students now use school issued mobile devices, including smartphones and tablets. [1]
- Previous studies have compared reading comprehension for physical and digital books. In some, no differences were found[2,3], but others show clear advantage for physical books. [4,5]
- Use of digital devices in schools for spatial tasks is also growing, but unlike with reading, there is no research on whether they are as effective as traditional analog versions.

Experiment 1: Comparing Digital & Physical Tasks

- Completing spatial tasks in digital environments may lead to different performance outcomes compared to physical versions.
- It is important to understand whether completing spatial tasks on digital interfaces leads to performance comparable to that of physical interfaces, and whether they maintain related advantages. For example, engaging in physical spatial tasks has been shown to improve later arithmetic performance in children. [12]
  - **GOAL: Compare performance on physical & digital spatial problem-solving task interfaces and also assess later effects on math performance.**
  - We expected performance using the physical task interface to surpass the digital version. We also expected those in the physical task condition to perform better on a subsequent math test.

Experiment 1: Method

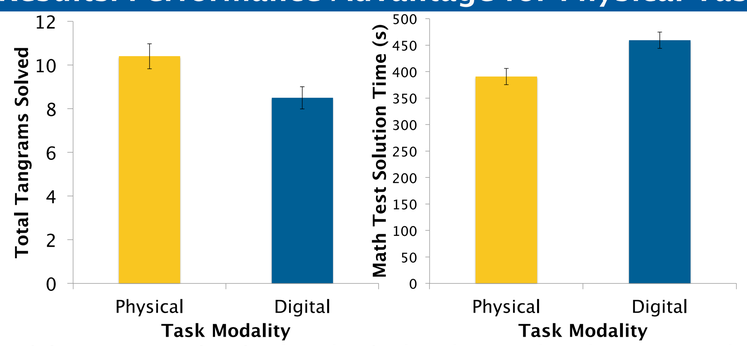


Participants (N = 180) were randomly assigned to complete tangrams using a **digital** tablet-based interface or using a **physical** table-top version.

All participants were given the same tangram templates. Following the tangram task, participants were asked to complete 50 addition and subtraction problems.

Measures: Total **Tangrams Solved**, Math **Test Solution Time**

Results: Performance Advantage for Physical Task



Participants engaging in the physical task completed more puzzles than those using the digital task, $t\,(179) = 2.48$, $p = 0.01$. Physical task performance also yielded a subsequent solution time advantage for the math test, $t\,(179) = -3.16$, $p < 0.01$.

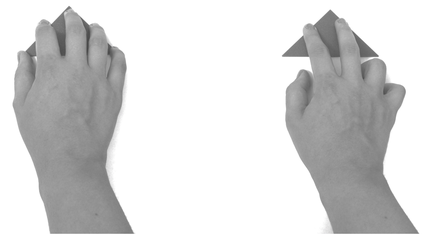
What Drives These Performance Differences?

- Differences in affordances between physical and digital interfaces may have influenced performance directly, or may have led to critical differences in mental representations.
- External representations play an integral role in distributed cognitive processes by facilitating different types of exploratory and solution-directed actions. [6,7,8]
- Tangible user Interfaces provide engagement and performance benefits by allowing for more embodied interactions. [9,10,11]

Experiment 2: Limiting Physical Interfaces

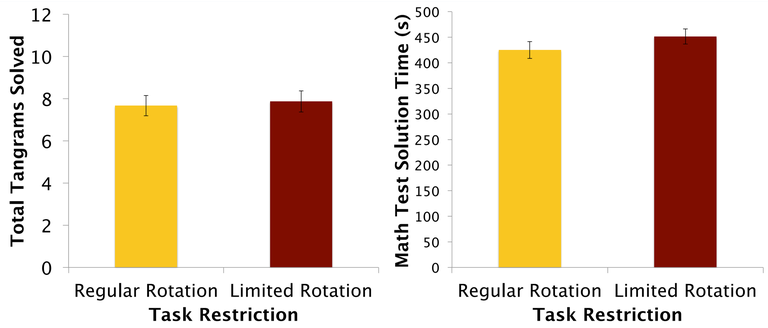
- Experiment 1 results may be driven by the difference between the familiar rotational interactions allowed by the physical paradigm and the more constrained rotation technique afforded by the tablet.
  - **GOAL: Assess spatial problem solving performance using the physical interface from Experiment 1, but constrain physical interaction to that allowed by the tablet interface.**
  - Outcome A: Performance differs due to rotational constraints. Experiment 1 findings are due to interactional limitations.
  - Outcome B: Rotational constraints do not affect performance. Experiment 1 findings are due to representational differences.

Experiment 2: Method



Participants (N = 138) were tested using only the physical interface. Half interacted with the tangrams **without restriction** and half were asked to use a two-finger **limited rotation** technique that mirrors interactional limitations of the tablet computer. The same performance measures were collected.

Results: No Effect of Rotational Restriction

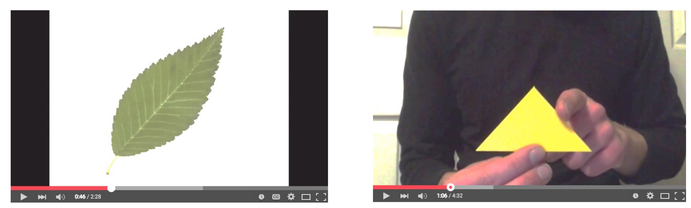


Performance on the tangram task was not affected by restricting rotation of the individual pieces, $t\,(137) = -0.29$, $p = 0.78$. Math test solution time was also unaffected, $t\,(137) = -1.19$, $p = 0.24$.

Experiment 3: Priming Spatial Representations

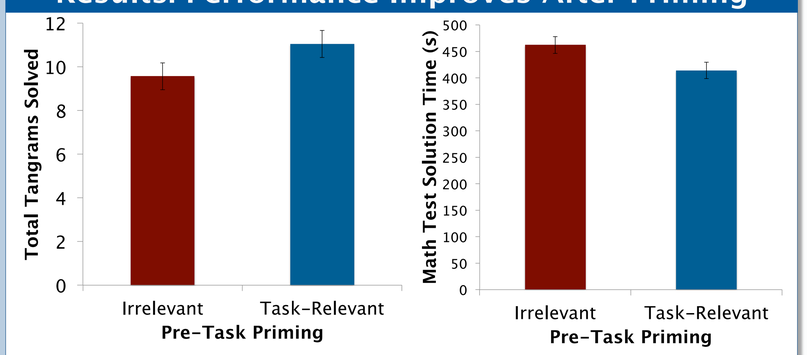
- Experiment 2 results suggest that the physical task advantage shown in Experiment 1 is more likely due to representational differences than physical differences between interfaces.
- Children tend to adopt different problem solving strategies based on the affordances primed by virtual and physical objects. [8] Differences in the physical affordances of a system encourage different types of information-seeking actions. [10]
  - **GOAL: Vary the degree to which task-relevant spatial representations are primed and measure the influence on task performance and later math performance.**
  - Increased priming of task-relevant spatial representations should increase spatial problem solving performance.

Experiment 3: Method



Participants (N = 132) watched an instructional video and then completed digital tangrams. Half of the participants watched an **irrelevant control** video, while the other half watched a **task-relevant priming** video describing each tangram piece. The participants then engaged in the tablet-based digital tangram task and completed the arithmetic test. The same performance measures were collected.

Results: Performance Improves After Priming



Participants who watched the task-relevant priming video completed more tangrams than participants who watched the irrelevant control video, $t\,(131) = -1.689$, $p = 0.045$. Participants who received task-relevant priming also performed faster on a later math test, $t\,(131) = 2.176$, $p = 0.015$.

Summary & Discussion

- Participants demonstrated a performance advantage when interacting with a physical table-top spatial task compared to a digital tablet version. Using the physical task also led to faster solution times on a later arithmetic test.
- The advantage for the physical task could not be explained by the rotational constraints of the tablet interface.
- Richness of spatial representation, achieved through visual priming of spatial information, led to enhanced tangram performance. Spatial representation priming may also drive the speed advantage in the arithmetic test.
- The 3D nature of the physical task inherently primes spatial representation, facilitating performance. Because the tablet does not allow for such priming, a pre-task spatial priming video could be used to mitigate tablet limitations.
- Isolating the specific affordances that drive these benefits improves our understanding of distributed cognition, and suggests guidelines for the more appropriate and effective use of digital technology in the classroom.