Perceptual Benefits of Physical Material for a Spatial Task

Abstract: We explored the perceptual benefits of using tangible objects for a spatial problem-solving task. In two experiments, thirty-three participants completed the Paper Folding Test (Ekstrom, French & Harman, 1976) with either a physical or abstract representation of the material: we found that subjects (females, in particular) were faster and more accurate in solving the test using physical material. The results of this study are discussed in terms of perceptual benefits of manipulatives for education.

Introduction

According to a situated view of cognition, knowing is inseparable from doing. People actively use external resources to solve problems they face, by manipulating and combining objects in their environment. As Shirouzu (2002) states it, "Initial solutions to problems in the outer world may depend heavily on (or may take full advantage of) what is available in the external environment at the given time and space". This view is supported by a long tradition of using manipulatives to teach mathematics (e.g. Montessori, 1964), which has been empirically assessed by an important number of authors. Sowell (1989), for example, showed in a meta-analysis of 60 studies that manipulatives lead to a higher math achievement and a better attitude toward this discipline than the use of diagrams and symbols. More recently, Martin & Schwartz (2005) proposed that learning with physical actions can have various benefits depending on the flexibility of the environment and the student's ideas: for expert students, the main advantage of a stable environment is mainly to off-load the cognitive burden of a task, while novice students would take advantage of a less stable environment to reinterpret the situation in many ways until they find an acceptable solution.

However it is not clear whether the benefits from using a physical material come solely from manipulating objects, or if external resources have other advantages (e.g. perceptual). For a variety a situations, it may be that physical objects just give a better conceptual anchorage compared to abstract material: because of the perceptual concreteness of the material, students may better be able to relate to the problem at hand with their personal experiences, and thus propose a larger diversity of solutions. We propose to test this hypothesis by using a problem-solving task (a paper-folding test, which is usually used to measure spatial abilities) with either a abstract or physical material as instructions. If our hypothesis is correct, subjects should solve the problem more quickly and more accurately with real sheets of paper compared to the same task represented in an abstract way. This pattern of results would show that manipulatives not only help students to better understand a problem by manipulating physical objects, but also by offering a better perceptual representation of the situation.

General Description of the Experiment

We used a within-subject design to test our hypothesis. Each subject solved eight problems of the Paper Folding Test (Ekstrom, French & Harman, 1976), and we randomly assigned each problem to one representation for each subject (abstract or physical). We measured how many trials and how much time each participants needed to complete the task; moreover we observed the strategy used by each subject (verbalizations, gestures) to give us further insight about their cognitive process during the task.

In this experiment, we used time as a measure of the cognitive load induced by the task. We assume that the longer a subject will take to solve the problem, the bigger the cognitive load will be. As a consequence, our main hypothesis is that subjects will complete the task faster if they use a physical representation compared to an abstract one.

Methods

Participants

34 subjects took part in this experiment (19 females, 15 males; mean age = 29.2, SD = 4.9). All of them were graduate students and were selected from acquaintances of the experimenter.

Material

We choose to use the Paper Folding Test designed by Ekstrom, French & Harman (1976) to test our hypotheses. This test measures spatial ability by asking the subject to mentally unfold a sheet of paper; the item on the top of figure 1 is an example of a Paper Folding question. The instructions on the left depict how the paper has been folded; on the last image, a hole is punched on the sheet. The task of the participant is to choose the correct pattern on the left if the sheet is unfolded. In our case, the last 8 items of the Paper Folding Test were chosen because of their relative difficulty.

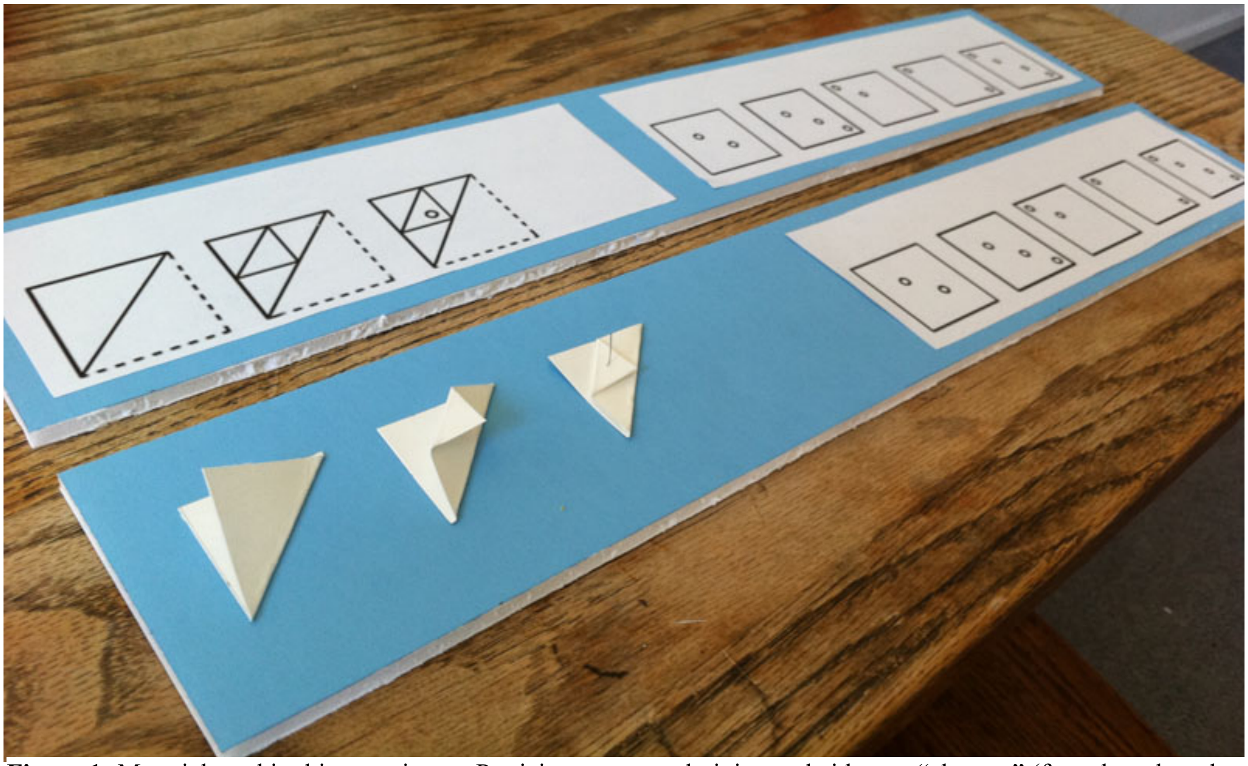


Figure 1: Material used in this experiment. Participants were administrated either an “abstract” (foam board on the top) or a “physical” (foam board on the bottom) version of the item.

Design

A within-subject design allowed us to control for non-relevant variables (demographic characteristics and spatial ability of the subjects). Each participant went through the 8 items individually, alternating between physical and abstract material). We randomized the order of the items and the kind of presentation to neutralize order and position effects.

Procedure

Subjects were run individually in a sound proof room. Upon their arrival, the experimenter thanked them for their participation and asked them to fill a questionnaire with demographic questions (age, gender, occupation). Then, the experimenter explained them that two tests would challenge their spatial skills. They were also told that some items would be difficult for them. The experimenter then presented them the first two pages of the Paper Folding Test: on the first sheet, every step of the folding is made explicit to ensure that the subject understands the flow of the task. The same procedure was used as for first test: the experimenter first explained the goal of the task and how to solve, and the subjects had to solve two trial items while they were thinking aloud. Once it was clear that the subjects understood the task, the experimenter presented them the different material used in this study with an example item: an abstract representation (taken straight from the original Paper Folding Test), and a physical representation (real sheets of paper folded). Subjects were also warned that if they picked up the wrong answer, they would have to try again until they would find the right solution. They were also asked to think about the problem before proposing another answer, and not choose a random solution. The experimenter then presented 8 problems (one at a time) in a random order and with a random presentation (abstract or physical) and measured the time required to solve each problem. Finally, the subjects were again thanked for their participation and accompanied to the exit of the building.

Results (study 1 and 2)

This experiment has been first conducted with 16 participants, and then replicated with 18 additional subjects. Since the two studies had similar procedures, we decided to merge the two datasets together and present our findings as one result.

Main result

Our results supported the hypothesis that subjects were faster to solve spatial problems when using physical material: $F(1,33) = 13.04$, $p < .001$. In average participants needed 36.24 sec. (SD = 8.5) with abstract material, while they could solve similar problems in 25.87 sec. (SD = 6.2) with physical material (see figure 2).

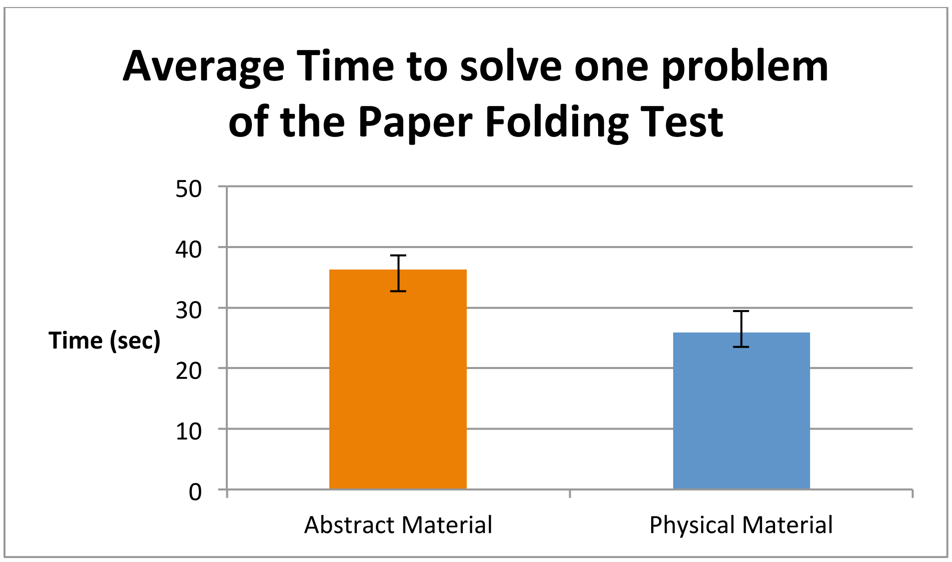
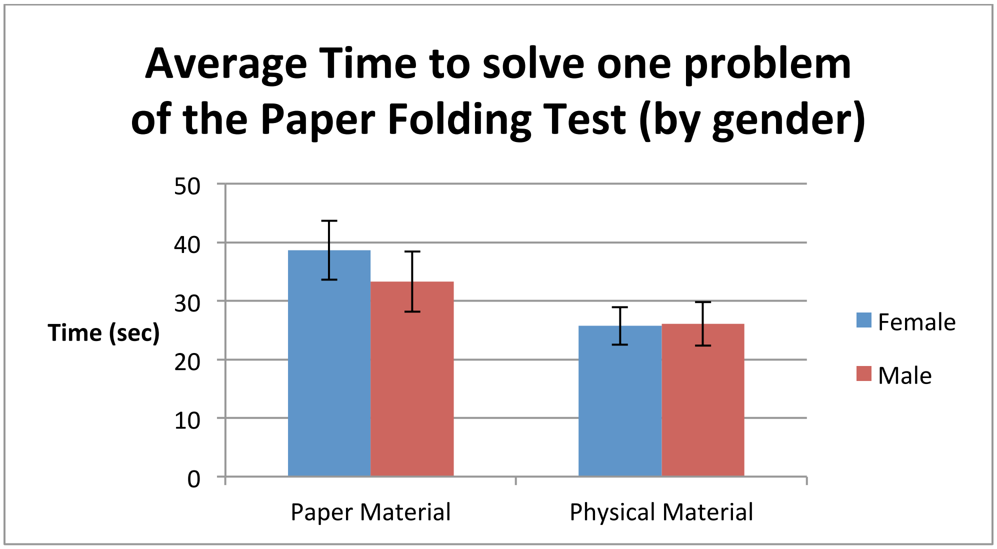


Figure 2: Main results of the experiment. Using a within-subjects design, participants were asked to solve spatial problems (see the Paper Folding Test, appendix 1) using either abstract or physical instructions. Subjects seeing real sheets of paper folded (physical condition) were faster in solving the task.

Results related to gender

Interestingly, using physical material was beneficial for women ($F(1,18) = 8.24, p < .01$) but not for male subjects ($F(1,14) = 2.39, p = .15$). Females took in average 6 additional seconds to solve a problem (compared to men), even though this result is not significant ($F < 1$).



It should also be noted that 22 subjects out of 34 benefited from using physical material; among those 22 participants, 13 were females and 9 were males. Thus, the main effect of this experiment does not seem to be carried only by a few participants. On the opposite, a majority of subjects (65%) were in average faster when solving problems with physical material.

Qualitative observations

Participants produced a variety of behaviors during the task. Globally, three kinds of strategies emerged: the first one was to use the subject's own body as a way to simulate the unfolding of the sheet of paper. One participant, for instance, would use her two hands as a symbolic sheet and mimicked the folding by joining her hands together. The second strategy was to exploit the 3D property of the physical material: even if the participants were not supposed to touch the model, some of them needed to compress the physical material to appreciate the resistance of the sheet of paper and the different representations offered by the level of compression; this was usually accompanied by a movement of the head (lowering it) in order to get an alternative vantage point of the problem. Finally the third strategy involved counting the number of times the sheet of paper was folded and inferring the number of holes present on the final pattern of results. This approach was usually not successful, since the correct solution frequently shared the same number of holes with other items. While we do not have quantitative data on those observations, it should be noted that those three strategies were more likely to be used be female participants; male subjects, on the other hand, did not seem to gesture or think aloud as much.

Discussion

The main finding of this study is that manipulatives help to solve a spatial problem on a perceptual level. More specifically, it seems that females in particular are better able to take advantage of the physicality of the material.

One interpretation is that physical material allows for "epistemic actions": namely, "actions whose purpose is not to alter the world so as to advance physically toward some goal (e.g., laying a brick for a walk), but rather to alter the world so as to help make available information required as part of a problem solving routine. Examples of epistemic actions include looking at a chessboard from different angles, organizing the spatial layout of a hand of cards . . . laying out our mechanical parts in the order required for correct assembly, and so on" (Anderson, 2003). Like chess players looking at the chessboard from various angles, our female subjects were particularly good at looking at our test items from different vantage points to help them understand how the model was built.

Another interpretation is that females may be more likely to rely on surfaces features, which is a double-edged sword for a spatial task. Indeed, when the representation is close to reality female participants do not seem to have any trouble to solve the problem at hand; however, when the surface features are confusing they have much more difficulty figuring out the right solution. As a consequence, we can imagine that training some subjects to extract the deep structure of a problem to help them perform better at this task.

Finally, we found interesting differences in terms of strategies deployed by the participants. Some subjects did not feel the need to use compensatory strategies, while others expressed a variety of behavior during the task (gesturing and vocalizing). We interpret this as a perceived level of difficulty: subjects who felt comfortable with this task (either because they have a more efficient working memory or better spatial skills) did not need to create physical crutches to solve the problem, while subjects who were less confident automatically tried to change their environment to simplify the problem they face. The strategies used varied from physical simulation (hands gestures) to some logical reasoning (for more detail about the role of gestures in solving the paper folding test, see Chu & Kita, 2011).

Implications for Education

This study has several implications for education: for example, teaching chemistry usually involves working with complex 3D molecules. For instance, it would be interesting to explore whether graphic displays of molecules that include more perceptual clues such as shading would enhance the level of performance in chemistry. We also propose that some students (females, in particular) may benefit form a customized curriculum and potentially be trained to transition from a physical to an abstract representation in order to extract the deep structures of a problem. Finally, future studies should also test whether it is possible to teach students to extract the deep structure of a problem and rely on this mental model to perform a task. Indeed, it may be possible that those skills 1) are innate, and thus cannot be changed; or 2) necessitate en extensive training (e.g. several hundreds of hours) to be improved.

References

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Appendix

1. The 8 original items used for this experiment