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SHORT REPORT

The spatial thinking of origami: evidence from think-aloud protocols

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Abstract Origami, the ancient Japanese art of paper folding, involves spatial thinking to both interpret and carry out its instructions. As such, it has the potential to provide spatial training (Taylor and Hutton under review). The present work uses cognitive discourse analysis to reveal the spatial thinking involved in origami and to suggest how it may be beneficial for spatial training. Analysis of think-aloud data while participants folded origami and its relation to gender, spatial ability measures, and thinking style suggest that one way that people profit from spatial training is through the possibility to verbalize concepts needed to solve-related spatial tasks.

Keywords Spatial thinking · Think aloud · Cognitive discourse analysis · Origami

Educational "Back to Basics" focus on the three Rs: reading, (w)riting, and (a)rithmetic. However, this list misses a foundational cognitive skill: visuospatial thinking, which underlies reasoning in many science, technology, engineering, and mathematics (STEM) domains (Uttal et al. 2012). Indeed, measures of spatial ability correlate with success in many STEM areas (e.g., Hegarty et al. 2010), including medicine (Keehner et al. 2004), physics (Sorby 2001), chemistry (Coleman and Gotch 1998), mathematics (Casey et al. 1997), engineering (Peters et al. 1995a), and geology (Orion et al. 1997). Even elementary STEM education evokes spatial thinking through geometry, missing-term arithmetic problems, and graph/map understanding. Yet, spatial thinking is largely absent in U.S. elementary school curriculum (NRC 2006). Could origami be used to train spatial thinking in elementary school? The present work explores the spatial thinking integral to origami, one element of a novel, elementary-age spatial training program (Taylor and Hutton under review). Through this work, we suggest that one way people profit from spatial training is by building a vocabulary through which they can verbalize concepts needed to solve-related spatial tasks.

Origami, the Japanese art of paper folding, combines basic folds to create 3-D objects. Embedded in origami are opportunities for visuospatial thinking. While folding a model, one can visualize the completed model throughout the folding steps and thereby see the connection between the folds and the completed model. Further, origami imbeds visuospatial thinking in its instructions, both verbal and graphic, including reversing, rotating, and inverting a model, or translating steps to the mirror side. From the folding process, visuospatial concepts emerge, such as the elemental mountain and valley folds.

The present study sought to capture evidence of visuospatial thinking, while individuals engage in origami. Participants were asked to *think aloud* while following origami instructions to fold a tulip, the stem, and blossom. To capture the cognitive processes evident during folding, we used cognitive discourse analysis (CODA; Tenbrink

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2008). CODA uses linguistic discourse analytic methods to highlight structures and patterns in a speaker's utterances. These methods can capture deeper insights into cognitive processes, even those speakers might not be able to consciously verbalize.

Twenty-four Tufts University undergraduates, all native English speakers, participated. They folded the origami tulip, first the stem and then the blossom, thinking aloud, while they folded. Then, they completed a task wherein they determined which of three origami objects matched the crease patterns of an unfolded object, while thinking aloud. Finally, they completed three spatial abilities tests: the re-drawn Vandenberg and Kuse mental rotation (Peters et al. 1995b), mental paper folding (Shepard and Feng 1972), and the Santa Barbara Solids Test (Cohen and Hegarty in press). Here, we focus on the cognitive processes evident in verbalizations while folding the stem and their relation to other measures potentially reflecting cognitive processing. In particular, we identified emerging spatial concepts by identifying *new spatial terms* used by the participants (i.e., spatial terms not included in the corresponding instruction), as well as (within a range of content categories) utterances that reflected *conceptual additions to the instructions*. We measured origami success with independent ratings (7-point scale) of pictures of the origami tulips. We eliminated one participant from all analyses for difficulty with the origami task, as determined by success scores greater than 2 standard deviations below the mean. Analysis consisted of correlations between variables of interest using Spearman's rho.

In the results, the use of *new spatial terms* suggests that having these terms cognitively available impacts conceptualization of the origami task. Central to this conclusion is that use of new spatial terms when folding correlated with success in the other origami-related task, matching origami objects to crease patterns ($r = 0.486$, $n = 23$, $p < .05$). Additionally, new spatial terms dominated the types of conceptual additions participants mentioned when folding. These conceptual additions go beyond what the instructions provided. People described the folding procedures spatially and in ways not mentioned in the instructions, as in "fold it in half" or "fold the lower tip onto the upper one;" they compared actions within and across steps or discussed the crease, object alignment, or object orientation. Inclusion of these conceptual additions all positively correlated with new spatial term use (all $r > 0.42$, $n = 23$, all $p < .05$). Overall, male participants tended to add such spatial information to a greater extent than did females ($r = 0.443$, $n = 23$, $p < .05$). Other results showed relationships between time needed to fold the stem and spatially orienting during folding, including explicit reference to the object's orientation ($r = 0.529$, $n = 23$, $p < .01$) and to the picture in the instructions ($r = 0.436$, $n = 23$, $p < .05$). Finally, time to fold the stem was marginally correlated with folding success of the tulip ($r = 0.397$, $n = 23$, $p = .06$).

The relationship between using new spatial terms, extension of thinking beyond that offered by the instructions, and success in a subsequent spatial reasoning task suggests the importance of spatial concepts for spatial tasks. This finding has important implications for spatial training. Notably, it suggests that spatial training that includes spatial concept vocabulary, particularly spatial transformations, helps build a spatial thinking foundation that may be transferrable. This is consistent with research showing that labels enhance concept learning (Lupyan 2008). Such conceptual transfer may also underlie individual differences, including gender, in spatial ability. STEM education can profit from this point as successful reasoning for many STEM topics involves spatial thinking, albeit a range of specific spatial thinking across disciplines (Atit et al. in press; Harris et al. in press). Origami, the instructions for which provide the verbal and visual language for spatial transformations, has this potential. A hint of this potential has been shown in spatial thinking gains children showed after completing a program of origami and paper engineering (Taylor and Hutton under review). Further, children applied concepts gained when learning origami to tasks involving paper engineering, showing application of their conceptual base to another spatial task. Thus, spatial training programs that combine training of skills and learning of concepts may be particularly effective.

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