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Specificity of mental transformations involved in understanding spatial structures

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A B S T R A C T

Spatial abilities are thought to play an important role in learning from visualizations. The specificity of spatial abilities for particular mental transformations involved in spatial learning from visual media (rotation, perspective taking, spatial integration) was investigated. For each of the transformations, a dedicated criterion task was constructed and a specific ability was measured. Furthermore, reasoning ability (g) was considered. Hierarchical multiple regression analyses and simultaneous decompositions of variance were utilized. Mental rotation was a specific predictor of the rotation transformation, perspective transformation was predicted both by perspective taking ability and visual-spatial working memory (VSWM) capacity, and mental integration was predicted by reasoning ability, but not by VSWM capacity, contrary to expectations. It is concluded that correspondences between criterion tasks and ability measures may differ although links between ability and task requirements appear conceivable.

1. Introduction

Multimedia instructions typically include detailed visualizations of the subject matter. In order to understand the visualizations, learners perform spatial transformations mentally (e.g., they imagine alternative views on objects, or they mentally animate processes in a complex system, Hegarty, Kriz, & Cate, 2003; Münzer, Seufert, & Brünken, 2009). Individual differences in learner's abilities to perform mental spatial transformations might therefore be crucial. Accordingly, correlations between spatial ability measures and learning outcomes suggest that spatial abilities play an important role in learning with visualizations (see Höffler, 2010, for a review). Moreover, visualizations might be optimized such that learning processes of individuals with lower spatial abilities are facilitated (Höffler, 2010; Münzer, 2012, 2015).

However, mere correlations between spatial abilities and learning outcomes do not allow to draw conclusions about the actually performed mental transformations during learning. Problems concerning the validity of those conclusions occur (1) if mental spatial transformations during learning are not identifiable and/or relations between spatial ability measures and learning outcomes appear unsubstantiated and (2) if issues of discriminant validity are not considered.

The present study investigates the relations between spatial abilities and spatial mental transformations actually performed with visualizations. To this end, the study focuses on particular tasks that involve identifiable mental spatial transformations. These spatial transformations are pertinent to the understanding of complex spatial structures which are shown as two-dimensional static pictures in learning materials in many domains (e.g., mechanical systems, anatomy, architecture, etc.). The spatial mental transformations are (1) rotation of objects, (2) shift of spatial perspective, and (3) integration of different parts. In addition, the present study considers discriminant validity by examining the *specificity* of the relation between a spatial ability measure and a corresponding task. That is, task performance should be predicted by a corresponding spatial ability measure, but not by other (spatial and/or general cognitive) measures (e.g., imagined rotation should be predicted by mental rotation ability but not by the capacity of working memory or by general inductive reasoning ability).

1.1. Spatial abilities in learning from visualizations

Individual learners differ in spatial abilities, i.e., in mentally storing and manipulating mental visual-spatial representations (see Hegarty & Waller, 2005, for a review). There are different sub-factors of spatial ability. A fundamental distinction concerns the involvement of the body axes to perform spatial tasks. Spatial *visualization* involves mentally manipulating objects without reference to one's body axes, whereas spatial *orientation* involves changes of oneself's perspective or viewpoint (Thurstone, 1950). Lohman (1979, 1988) distinguished three spatial factors, (1) speeded rotation of simple items, (2) spatial orientation (involving perspective change), and (3) spatial visualization (referring

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to complex materials and sequences of transformations). Carroll (1993) identified five main factors based on extensive data sets, (1) "spatial visualization" involving complex and multi-step spatial transformations, (2) "spatial relations" requiring mental rotation with simple figures under speeded instruction, (3) "closure speed" requiring quick recognition of incomplete figures, (4) "closure flexibility" involving identification of hidden figures in complex spatial patterns, and (5) "perceptual speed" requiring speeded comparisons of simple figures.

It seems conceivable that individual differences in spatial abilities play an important role in learning with visualizations. Spatial abilities appear to be particularly important for specializations in STEM domains (Wai, Lubinski, & Benbow, 2009). Substantial correlations between measures of spatial abilities and outcomes of learning have been found in various domains in which learning materials depend on visualizations, for instance, in medical and dental education (e.g., Hegarty, Keehner, Khooshabeh, & Montello, 2009) or in learning about spatial layouts (Hegarty, Montello, Richardson, Ishikawa, & Lovelace, 2006; Münzer & Stahl, 2011; Waller, 2000).

How exactly are spatial factors thought to be involved in learning? Learning outcomes often address domain-specific thinking, problem solving, and cognitive schema construction. Höffler (2010) reviewed the role of spatial abilities in multimedia learning with visualizations, considering 27 experiments from 19 primary studies. The meta-analysis suggested a medium advantage of high-spatial ability learners over low-ability learners. Moreover, it was found that dynamic visualizations (i.e., animations instead of static pictures) as well as three-dimensional (vs. two-dimensional) visualizations could compensate for lower spatial ability (Höffler, 2010). The meta-analysis examined a moderating role of the spatial factor measured ("visualization" versus "spatial relations"). However, a moderating role of spatial factors was not obtained "although they have been identified previously as two distinguishable facets of spatial ability" (Höffler, 2010, p. 262).

Participants in the primary multimedia learning studies included in the review by Höffler (2010) typically performed the paper folding test (PFT, Ekstrom, French, Harman, & Dermen, 1976), the mental rotation test (MRT, Vandenberg & Kuse, 1978), or the card rotation test (Ekstrom et al., 1976). The multimedia instructions covered various domains (mechanical systems, cell biology, spatial layout learning, mathematics, basic electronics and second language learning, etc.). The instructions deployed different methods (e.g., multimedia learning with visualizations and with/without verbal narration, learning with/without interactive control, or learning by navigating in a virtual environment). Thus, quite a small selection of standard spatial ability measures was utilized, and these measures were apparently thought to account for a wide range of learning outcomes in various domains.

Apparently, the few spatial ability measures might have served as rather "broad" predictors of various learning outcomes. The finding that the relation between ability measure and learning outcome was independent of the represented spatial factor (i.e., a moderating role of spatial factors was not found) indicates that those spatial measures did not account for more specific information-processing requirements of a learning task. It seems that ability measures were not carefully selected with respect to actual mental processes during learning.

Furthermore, it might be questioned whether the typical measurements of spatial abilities are valid with respect to the processes involved. Both the PFT and the MRT are representative of the "spatial visualization" factor, i.e., the broad spatial factor that involves multiple steps of mental transformations (Carroll, 1993). In contrast to its description as a "mental rotation test", the MRT is thought to measure the visualization factor rather than spatial relations (Pellegrino, Alderton, & Shute, 1984). Importantly, tests addressing the spatial visualization factor, including PFT and MRT, can often be solved in different ways (e.g., holistic or analytical, Kyllonen, Lohman, & Snow, 1984). Linn and Peterson (1985) noted that "different processes may contribute to performance" in the MRT (Linn and Peterson, 1985, p. 1484). Geiser, Lehmann, and Eid (2006) were able to separate "rotators" from "non-rotaters" in the MRT and identified an analytic strategy. Thus, analytical, (i.e., non-spatial) mental processing may be involved in attempts to solve those tasks. Therefore, general aspects of intelligence may play a role both in the spatial ability measures as well as in outcomes of learning. Given this ambiguity, discriminant validity needs to be demonstrated to draw conclusion about the involvement of *spatial* ability in learning from visualizations.

1.2. Mental spatial transformations in understanding spatial structures

The present study aims at investigating a more specific involvement of spatial abilities in learning with visualizations. For this purpose, visualizations of spatial structures are chosen as learning materials. A spatial structure is a typically three-dimensional complex object that has several connected parts with fixed spatial relations. In many domains (e.g., architecture, geography, chemistry, medicine, engineering, mathematics), studying such spatial structures (e.g., a multi-level building, a molecule, the anatomy of the human body, an engine) is an essential part of learning. In visualizations, spatial structures are presented in a "small-scale", two-dimensional format with selected pictures that show parts of the structure from different viewpoints, in different detail, with cross-sectional views, etc. In order to understand the spatial structure, specific spatial mental transformations must be applied during learning.

Three spatial transformations are considered: (1) *mental rotation*, (2) *perspective taking*, and (3) *mental integration*.

Mental rotation means that learners attempt to understand how an object would look from another viewpoint. The object is mentally rotated. Reaction times of identity judgments between an original object and a rotated comparison object depend almost linearly on the amount of the rotation (Shepard & Cooper, 1982; Shepard & Metzler, 1973). Therefore, mental rotation can be viewed as an analogous ("Gestalt-like") cognitive process. Mental rotation is associated with motor processes (e.g., Jansen-Osmann & Heil, 2007; Wexler, Kosslyn, & Berthoz, 1998; Wiedenbauer, Schmid, & Jansen-Osmann, 2007; Wohlschläger & Wohlschläger, 1998). This emphasizes the specificity of the mental rotation process and its analogous character. Factor-analytic studies have revealed distinct mental rotation ("spatial relations") and spatial visualization factors (Carroll, 1993; Lohman, 1988).

Perspective taking means that learners attempt to imagine taking a place within a spatial scene involving a particular orientation (heading) while actually viewing the scene from an external viewpoint. The self is mentally re-oriented. This transformation corresponds to the spatial factor "spatial orientation" (Lohman, 1988; Thurstone, 1950). It seems as if this spatial transformation is particularly relevant for "large-scale" spaces where individuals can imagine "being part of it" or "move through it". However, research on learning from visualizations suggests that visual-spatial memory is generally viewpoint dependent (e.g., Garsoffky, Huff, & Schwan, 2007; Huff, Jahn, & Schwan, 2009), and that changes of viewpoint are separable from mental rotation (Hegarty & Waller, 2004; Zacks, Mires, Tversky, & Hazeltine, 2000).

Mental integration means that learners learn about several parts of a spatial structure and mentally integrate those parts into the larger structure. The overall spatial structure may not be visible when detailed views of parts of the structure are shown. When the overall structure is presented, then detail information is not visible. When studying a particular part of the spatial structure to obtain more detailed information, learners thus have to memorize the location of that part within the larger structure. Mental integration is the process of integrating several detail-location associations into one larger, coherent spatial structure. Spatial mental integration is not captured by the spatial factors described above, but visual-spatial working memory has been appraised as a key factor in learning about complex spatial configurations, because different parts of the configuration have to be maintained and mentally integrated (Hegarty et al., 2006; Münzer, Zimmer, & Baus, 2012).