Spatial Ability's Influence on Learning with Visualizations – a Meta-Analysis

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Abstract. This meta-analysis focuses on the role of spatial ability when learning with pictorial visualizations. Regarding 27 different experiments from 19 studies, several sub-factors of spatial ability are considered as well as dynamic and non-dynamic, interactive and non-interactive visualizations. An overall effect of r=.34 (95%-*CI* .28 to .39) demonstrating a medium advantage for high-spatial ability learners when working with visualizations is calculated. More importantly, two moderators could be identified: Learners with low spatial ability can be significantly supported by a dynamic instead of a non-dynamic visualization as well as by 3d- instead of 2d-illustrations. Results are discussed in consideration of contemporary theories of multimedia learning.

Keywords: visualization; spatial ability; meta-analysis; static pictures; animation.

Introduction

In educational practice, non-dynamic and, increasingly, dynamic visualizations are a common tool to support the learning process. While the positive influence of visualizations in general seems undisputed and well-documented (cf. Mayer, 2005), there is more skepticism as to dynamic visualizations. What is more, the role of individual differences increasingly shifts in focus: Do all learners profit equally from visualizations? And if not, how can those learners be supported? In this sense, the role of spatial ability on learning with visualizations is still rather unclear. Though, at first glance, an obvious moderator variable, previous studies did not find consistent results as to its role. Hence, the present meta-analysis aims at revealing if and in which way spatial ability influences learning with visualizations. While the meta-analysis itself is quite narrowly focused, the overall goal to demonstrate the importance of considering individual differences in learning is not.

Theoretical Background

When reviewing the literature on the role of spatial ability relating to learning with visualizations, a quite inconclusive and heterogeneous picture presents itself. While it seems to be beyond dispute that spatial ability plays a crucial role in multimedia learning (e.g., Hays, 1996) there are, for example, disagreements as to possible aptitude-treatment interactions. Hegarty (2005) offers the hypothesis that, in learning with dynamic visualizations (in contrast to non-dynamic visualizations), spatial ability might play the role of an enhancer: Learners with high spatial ability might profit from learning with animations, while learners with low spatial ability might not (*ability-as-enhancer* hypothesis). Later, however, Hegarty and Kriz (2008) found no such interactions in eight studies examining a mechanical device.

As another plausible hypothesis, some authors point out the possibility of a *compensating effect* for low spatial ability in that learners with low spatial ability might be supported by dynamic visualizations because the visualization provides the learners with an external representation of a process or procedure that helps them to build an adequate mental model; it should be unequally more difficult to construct such a model by using static pictures. Animations might therefore act as a "cognitive prosthetic" (Hegarty & Kriz, 2008) for learners with low spatial ability. Höffler, Sumfleth, and Leutner (2006) found such an effect for animations versus static pictures.

Moreover, many questions concerning possible moderating effects of the role of spatial ability are still open: If learner's spatial ability is low, how should the format of instruction be designed to support the learning process? For example, Huk (2006) found the role of 3d- versus 2d-visualizations important as to this question. Garg, Norman, and Sperotable (2001) indicated a possible compensating effect of self-paced versus system-paced visualizations.

On the whole, the role of spatial ability on learning with visualizations is still rather unclear and superficially defined; therefore, the present, narrowly focused meta-analysis is warranted and aims at examining the relations between spatial ability and different characteristics of visualizations more closely.

Method

A meta-analysis aims at integrating the findings of a larger number of studies, calculating overall-effects and identifying possible moderator variables. Specifically, overall-effects on learning outcomes of learners with high spatial ability compared to learners with low spatial ability when working with different types of visualizations were analyzed. For this analysis, a visualization is understood as any kind of non-verbal illustration, that is, pictures; graphs; diagrams; animations; and simulations. Furthermore, factors moderating the effect size were to be identified.

To identify relevant studies on the effects of spatial ability, the computerized databases *SSCI* (1993-2009) and *ERIC* (1966-2009) were searched (using the descriptors “spatial ability” or “spatial visualization” in combination with further relevant descriptors such as “animation”, “pictures”, “image”; “visualization”, “multimedia”, “graph”, “diagram”, etc). Apart from the articles found in databases, cross-references from identified articles helped to find some additional studies. However, for being able to include them in the meta-analysis, several criteria had to be fulfilled, for example the provision of the basic statistics needed for computing effect sizes. In the end, 19 articles (with 27 different experiments) remained.

Results

The overall effect of high-spatial ability learners versus low-spatial ability learners when using visualizations, disregarding all other variables, was calculated to be r=.34 (95%-confidence interval .28 to .39). This can be classified as a medium effect.

An overall homogeneity test indicated the overall effect size to be conditioned by one or more moderators: Q_{total}=99.05, df=58, p<.001. Therefore, moderator analyses for the variables described above were calculated. While 16 different features were coded, for example the type of spatial ability (spatial visualization, spatial relations, etc.), several characteristics of the visualization and the learning task as well as sample characteristics, only some highlights can be addressed here:

- When comparing high-spatial ability subjects and low-spatial ability subjects, a significant difference could be found between dynamic (r=.25, CI=.10 to .39) and non-dynamic (r=.41, CI=.28 to .52) visualizations ($z_{contrast}$=1.67, p<.05). That is, learners with high spatial ability are significantly more superior to learners with low spatial ability when learning with static pictures instead of animations.
- Another significant difference was found for the comparison of 2d- (r=.35, CI=.27 to .43) and 3d-visualizations (r=.23, CI=.09 to .36): $z_{contrast}$=1.68, p<.05. The introduction of a third dimension seemingly reduces the importance of a high spatial ability of the learner.
- As to the level of realism of the visualization, no significant differences were found.
- Concerning the role of interactivity, the comparisons between system-paced, self-paced, and highly interactive visualizations were not statistically significant.
- No significant differences were found between the measurement of declarative (r=.29, CI=.22 to .36) and problem-solving knowledge (r=.33, CI=.23 to .42) when comparing high- and low-spatial ability knowledge ($z_{contrast}$=0.56, p=.29).

Discussion and Conclusions

To summarize the results of the meta-analysis in one sentence: Spatial ability plays an important role in learning from visualizations (mean effect size *r*=.34), but is moderated by – at least – two compensating factors; learners with low spatial ability can be significantly supported by a dynamic visualization as well as a 3d-visualization.

Thus, it has been confirmed that spatial ability is a factor which should be considered when designing visualization experiments. Learners with low spatial ability can be supported by some design modifications of visualizations. The suggestion of the usage of 3d-visualizations (which leads directly to the controversial question of an "appropriate" level of realism) stands in contrast to other results (cp. Huk, 2006) and certainly warrants further examination. Other established notions about multimedia design (for example, the use of a secondary modality) could not be supported – which in no way contradicts those notions.

The suggestion to use dynamic visualizations for learners with low spatial ability, on the other hand, may sound controversial at first – but this finding could be *one* perfectly good reason for the many different findings concerning static pictures versus animations in the past (e.g., Höffler & Leutner, 2007; Tversky, Morrison, & Bétrancourt, 2002): Some learners (in this case, learners with high spatial ability) learn better when provided with non-transient static pictures which give them the opportunity to build their own mental model thanks to their highly developed spatial ability. And other learners (e.g., those with low spatial ability) seemingly learn better with animations; possibly because animations provide them with a ready-made dynamic mental model of the process shown.

Therefore, the present paper underlines the importance of the consideration of individual differences when learning with visualizations but also makes some contributions regarding design issues of learning environments.

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