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Evaluating the impact of depth cue salience in working three-dimensional mental rotation tasks by means of psychometric experiments

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ABSTRACT

The gender difference in three-dimensional mental rotation is well documented in the literature. In this article we combined automatic item generation, (quasi-)experimental research designs and item response theory models of change measurement to evaluate the effect of the ability to extract the depth information conveyed in the two-dimensional illustrations on (1) females and males test performance and (2) subsequent cognitive processes called upon in the course of working three-dimensional mental rotation tasks. On the basis of prior studies we hypothesized that experimentally increasing the salience of depth cues would lead to an improvement in respondents' test performance that is more pronounced in females than males. This hypothesis was tested and confirmed in the first study. In the second study we extended the experimental design to take respondents' mental transformation strategies into account. We hypothesized that increasing the salience of depth cues would also lead to changes in respondents' mental transformation strategies. One of the main findings of this study was an increased use of more efficient mental transformation strategies that was more pronounced in females than males. Furthermore, the induced shift to more effective mental transformation strategies accounted for a sizeable portion of the reduction of the gender gap. The implications of the results of both studies are discussed.

1. Introduction

Meta-analytic studies have indicated marked gender differences in mental rotation tasks in favor of males (cf. Linn & Petersen, 1985; Voyer, Voyer, & Bryden, 1995; Masters & Sanders, 1993). However, the effect size differs depending on task characteristics. For instance, the effect size was larger for complex three-dimensional mental rotation tasks ($d = .70$ to $d = .94$) than for two-dimensional mental rotation tasks ($d = .31$ to $d = .44$). This finding has been explained with the requirement to construct an accurate three-dimensional mental representation of the objects on the basis of two-dimensional illustrations. Support for this hypothesis was given by the fact that the dimension of the stimulus material (2D vs. 3D) affects the time required to construct a mental representation instead of the actual mental rotation process itself (cf. Shepard & Metzler, 1988; Bethell-Fox & Shepard, 1988). Furthermore, several studies have demonstrated that the formation of the mental model – commonly referred to as encoding process – correlates with individual differences in paper–pencil mental rotation task. On the other hand, individual differences in the speed of the actual mental rotation process turned out to be virtually unrelated to respondents' performance in paper–pencil mental rotation tasks (cf. Hooven, Chabris, Ellison, Kievit & Kosslyn, submitted for publication; Wiedenbauer, Schmid, & Jansen-Osmann, 2007). This pattern of findings has led some researchers to conclude that the observed gender difference in three-dimensional mental rotation may be in parts attributable to cognitive processes that occur *prior* to the actual mental rotation process.

Thus, in the next section we will outline research evidence that has indicated that (1) individual differences in the ability to extract depth cues from the two-dimensional illustrations, and (2) individual differences in respondents' encoding- and mental transformation strategies constitute prime candidates for the explanation of the observed gender difference in three-dimensional mental rotation (for an overview: Arendasy, Sommer, & Gittler, 2010).

1.1. Contribution of cognitive processes to the observed gender difference

The relevance of the ability to extract the three-dimensional information conveyed in the two-dimensional illustrations has been indicated in studies showing that mental rotation tasks become harder to solve if the items feature a high spatial complexity (cf. Arendasy & Sommer, 2010; Rettig, Hutwelker, & Hornke, 1989; Shepard & Metzler, 1988). Furthermore, females have shown to be more affected than males by spatial complexity in cases in which parts of the figure are covered up in a manner which leads to ambiguous depth cues (cf. Arendasy, 2005; Arendasy & Sommer, 2010; Rettig et al., 1989; Voyer & Hou, 2006; Voyer & Doyle, 2010). In addition to these studies there is also more direct experimental evidence on the importance of this cognitive process. For instance, McWilliams,

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Hamilton, and Muncer (1997) have demonstrated that the effect size of the gender difference in three-dimensional mental rotation tasks can be reduced when respondents work more realistic wooden figurines instead of classic paper–pencil-test items. In line with this finding Parson et al. (2004) have found a large effect size of the gender difference in a paper–pencil mental rotation test that was not existing when the same item material has been administered in a virtual reality environment. Similarly, Arendasy et al. (2010) reported that the gender gap observed in a paper–pencil mental rotation test decreased when respondents were allowed to work the items with the aid of LCD-shutter glasses. However, results obtained in prior studies are not entirely unequivocal. For instance, Arendasy (2000) and Arendasy et al. (2010) did not find a narrowing of the gender gap when red/cyan anaglyph glasses were used to help the respondents to extract the three-dimensional information. A possible explanation for these findings might be that a certain degree of salience of the depth information (= accessibility of the three-dimensional information conveyed in the two dimensional illustrations) is required to narrow the gender gap observed in paper–pencil mental rotation tests. Due to the small amount of experimental studies there seems to be a need to validate the finding that technical aids which facilitate the extraction of depth cues cause a narrowing of the gender gap observed in classic paper–pencil mental rotation tests.

Regarding the contribution of encoding- and mental transformation processes to the explanation of the observed gender difference the available research has indicated that females and males differ in the strategies used to encode and mentally transform three-dimensional mental rotation items. Furthermore, encoding and mental transformation strategies have shown to be closely linked to each other and are therefore hard to study in isolation (cf. Glück & Fitting, 2003; Khooshabeh & Hegarty, 2008). In general, the available research indicated that females use either an analytic encoding and transformation procedure, or a piecemeal encoding and subsequent mental rotation of object parts more often, while males have shown to resort more often to holistic encoding and subsequent mental rotation of the entire object (e.g. Arendasy, 2000; Arendasy & Sommer, 2011; Cooper, 1982; Glück & Fitting, 2003; Heil & Jansen-Osmann, 2008; Janssen & Geiser, 2010; Kaufman, 2007; Khooshabeh & Hegarty, 2008). These differences in females and males mental transformation strategies have shown to be rather stable across different item types (Janssen & Geiser, 2010). Furthermore, research indicated that mental transformation strategies differ in their effectiveness. In general, females have been found to resort to less efficient encoding and mental transformation processes more often than males presumably due to their incapability to utilize the more efficient mental rotation strategies (cf. Arendasy, 2000; Arendasy & Sommer, 2011; Glück & Fitting, 2003).

2. Formulation of the problem

Although the available research evidence indicated that both kinds of processes are important in explaining the observed gender difference, it is less clear how they interact. Most recent models of three-dimensional mental rotation hypothesized that these two processing stages are sequentially organized and effects at lower levels should take precedence (cf. Heil & Rolke, 2002; Just & Carpenter, 1985; Shepard & Cooper, 1982). Thus, the ability to extract the depth information from the two-dimensional illustrations should be of particular relevance. It might be that females difficulties in extracting the depth cues from the two-dimensional illustrations of the objects leaves them with an insufficient amount of cognitive resources to apply more demanding and effective mental transformation strategies. In order to test this hypothesis, we conducted a series of studies. If the ability to extract the depth information contributes causally to the observed gender difference we would expect to find a gender-specific effect of the experimental manipulation of the salience of the depth cues that leads to a narrowing of the gender gap. Although this hypothesis has been tested by Arendasy et al. (2010) we attempted to replicate their finding in the light of the partly inconsistent results obtained in prior studies.

In the second study we evaluated, whether experimentally varying ease with which the depth information can be extracted from the two-dimensional illustration also leads to a change in respondents' mental transformation strategies. More precisely, we tested the hypothesis that females would be more likely to use more efficient mental transformation strategies when the salience of the depth information has been increased. If this hypothesis is confirmed, individual differences in the ability to extract the three-dimensional information can be regarded to be causally related to the observed gender difference by enabling respondents to use more efficient mental transformation strategies, which had previously been beyond their capabilities (cf. Arendasy, 2000; Glück & Fitting, 2003).

2.1. Description of the three-dimensional mental rotation task

We used a three-dimensional mental rotation task that has been constructed on the basis of an extended version of the cognitive model proposed by Just and Carpenter (1985) using automatic item generation. Automatic item generation is an effective way of constructing large sets of items with predictable psychometric properties on the basis of a cognitive model. The cognitive model links processes to certain item design features, which are systematically varied to generate the items. This can also be done automatically, when the construction rules are implemented into a computer program (for an overview: Arendasy & Sommer, 2011; Embretson, 1998, 2005; Irvine & Kyllonen, 2002). In the present article endless loops were used as a common item format. This particular item format has shown to exhibit measurement invariance across gender and females and males were equally affected by item design features (Arendasy & Sommer, 2010). Thus, gender bias can be ruled out and the results can be interpreted in a more straight forward manner. Furthermore, the task has shown to load on a spatial abilities factor together with several other spatial ability tests; including cube comparison tasks and Sheppard–Metzler-figures (cf. Arendasy, 2000; Arendasy, Hergovich & Sommer, 2008). Most interestingly, in a study conducted by Arendasy (2000) the new three-dimensional mental rotation test exhibited a G_v loading similar in magnitude to Sheppard–Metzler-figures. Since a detailed description of the entire construction process and the psychometric properties of this task are beyond the scope of this article, the interested reader is referred to the relevant literature (cf. Arendasy, 2000; Arendasy & Sommer, 2010;

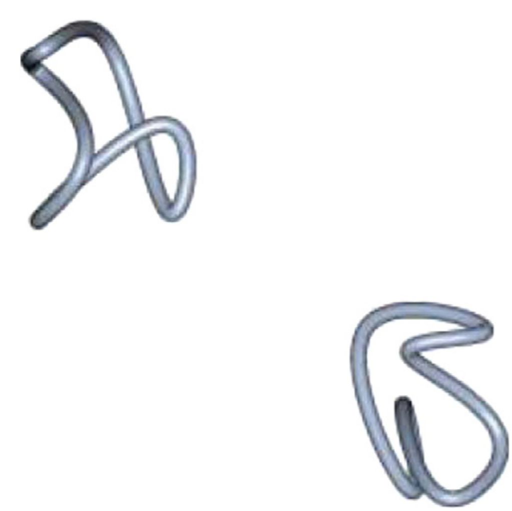

Fig. 1. Example of an automatically generated endless loop item with the reference figure on the left and the comparison figure on the right.