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The role of visual representation type, spatial ability, and reading comprehension in word problem solving: An item-level analysis in elementary school children

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ABSTRACT

This study examined the role of visual representation type, spatial ability, and reading comprehension in word problem solving in 128 sixth-grade students by using primarily an item-level approach rather than a test-level approach. We revealed that compared to students who did not make a visual representation, those who produced an accurate visual-schematic representation increased the chance of solving a word problem correctly almost six times. Inaccurate visual-schematic and pictorial representations, on the other hand, decreased students' chance of problem solving success. Noteworthy, reading comprehension was related to word problem solving at the test-level but not at the item-level. In interpreting the results, we advocate the use of item-level analyses since they are able to disclose such level-of-analysis discrepancies.

1. Introduction

Mathematical word problem solving has received a lot of attention in the scientific literature (e.g., Boonen, Van der Schoot, Van Wesel, De Vries, & Jolles, 2013; Cummins, Kintsch, Reusser, & Weimer, 1988; Hegarty & Kozhevnikov, 1999; Pape, 2003). Theoretical models converge on the idea that word problem solving is mainly composed of two phases: (1) the problem representation phase, which involves the identification and representation of the problem situation which is "hidden" in the word problem text, and (2) the problem solution phase, which includes the planning and execution of the required mathematical computations (e.g., Hegarty, Mayer, & Monk, 1995; Krawec, 2010; Lewis & Mayer, 1987; for an overview of the most significant theories on word problem solving, see Kintsch, 1998; Kintsch & Greeno, 1985). These models have led to the conclusion that students often struggle with solving word problems even when they perform competently on the computations required to solve these problems (Cummins et al., 1988; Lewis & Mayer, 1987; Schumacher & Fuchs, 2012). One of the problem solving skills children have been found to have difficulties with is the ability to generate an adequate visual representation of a word problem (Hegarty & Kozhevnikov, 1999; Van Garderen, 2006). However, we believe that the test-level-based approach which was used in quite a lot of the previous studies has some drawbacks. Therefore, the present study took a new, item-level, approach to gain a more complete understanding of the role of (different types of) visual representations in word problem solving.

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In previous studies, a positive relationship between visual representation type and word problem solving performance has been established by calculating correlations between the total amount of (specific) visual representations produced and the total amount of correctly solved word problems (e.g., Blatto-Vallee, Kelly, Gaustad, Porter, & Fonzi, 2007; Guoliang, 2003; Hegarty & Kozhevnikov, 1999; Krawec, 2010, 2012; Van Garderen, 2006; Van Garderen & Montague, 2003). However, calculating the correlation between two sum scores is an example of a test-level approach entailing limitations to be considered in this study. In particular, for three reasons, this correlation does not necessarily demonstrate that a certain type of visual representation has actually resulted in the correct answer to the word problem for which the visual representation was made. First, we have to consider that the established correlation between the total amount of (specific) visual representations and the total amount of correctly solved word problems might be explained by an underlying latent factor, such as a general measure of intelligence or cognitive ability (Boonen et al., 2013; Keith, Reynolds, Patel, & Ridley, 2008). Second, the relation might be explained by a mediating variable, for instance the capability of students to derive the correct mathematical operations from the visual representation and to determine the order in which these operations should be executed (i.e., the solution planning phase; see Mayer, 1985; Krawec, 2010). Finally, we have to acknowledge the possibility that a certain type of visual representation was made, but not used for answering the corresponding word problem. Ignoring this latter point may lead to an error of reasoning known as the *ecological fallacy*, where a researcher makes an inference about an individual based on aggregated data for a group (Lichtman, 1974; Robinson, 2009). For the purpose of the current study, it is important to recognize that a similar mistake is made when conclusions are drawn about performance on a specific item of a test (i.e., at the ''individual'' level) based on statistical analyses on the sum score of that test (i.e., at the ''group'' level). These considerations limit the conclusions we can draw with respect to the established relationship between visual representations and word problem solving performance.

Hence, we can conclude that the way in which the relation between (type of) visual representation and word problem solving performance was investigated in past research does not provide a decisive answer to the question if, and to what extent, visual representation type affects the chance of producing a correct solution to the word problem for which the representation was made. Taking the abovementioned considerations into account, we opted to investigate the importance of different types of visual representation for word problem solving success of students at the item-level rather than at the test-level. To achieve this, a change in statistical modeling was necessary. Previous studies used the sum scores at the test-level (i.e., the total amount of correctly answered word problems and the total amount of visual representations produced), which are continuous in nature and suitable for a linear regression model. However, in our study we used the scores on the item-level. These scores are categorical in nature and suitable for a logistic regression model, viz., for each item the answer is either correct or incorrect (dichotomous). Likewise, each visual representation which is evoked can be classified in one class of a set of categories (see below). Hence, our change in approach from the test-level to the item-level also meant that we opted for a logistic regression model instead of a linear regression model.

The item-level approach thus gave us the opportunity to examine if, and to what extent, the production of a visual representation affected the chance of successfully solving the word problem for which the visual representation was made (henceforth referred to as the *chance of problem solving success*). However, the chance of solving a word problem successfully is thought to be largely dependent on the *type* of visual representation that is produced (Hegarty & Kozhevnikov, 1999). In the present study three different types of visual representation were distinguished: pictorial representations, inaccurate visual-schematic representations, and accurate visual-schematic representations.

Generally, the production of pictorial representations involves the construction of vivid and detailed images (Hegarty & Kozhevnikov, 1999; Van Garderen, 2006). We expected to find that pictorial representations negatively affect the chance of problem solving success, as these representations merely concern images that encode the visual appearance of objects and persons described, and thus are irrelevant for the actual solution process (Hegarty & Kozhevnikov, 1999; Mayer, 1998; Van Garderen, 2006; Van Garderen & Montague, 2003. In line with the ''seductive details'' effect (Sanchez & Wiley, 2006), we hypothesized that forming a pictorial representation would divert the problem solvers' attention away from constructing a coherent (mental) model of the word problem, including the appropriate relations between the key variables. Visual-schematic representations, on other hand, do contain a coherent image of the problem situation hidden in the word problem, including the relations between the solution-relevant elements (Edens & Potter, 2008; Hegarty & Kozhevnikov, 1999; Kozhevnikov, Hegarty, & Mayer, 2002; Van Garderen & Montague, 2003). In contrast to the previously mentioned literature, however, in our study we made a distinction between two different types of visual-schematic representations. We hypothesized that only *accurate* visual-schematic representations would increase the chance of problem solving success, as in this visual representation type problem solvers infer the correct relations between the solution-relevant elements from the text base of the word problem and integrate them into a coherent visualization of the problem situation (Krawec, 2010). In *inaccurate* visual-schematic representations, these relations are also included but, in contrast to accurate visual-schematic representations, they are either incorrectly drawn or partly missing. It follows that this may put problem solvers on the wrong track in solving the problem (Krawec, 2010). Therefore, we expected to find that inaccurate visual-schematic representations would actually decrease the chance of problem solving success. An example of each visual representation type is given in Table 1.

At this point, it is important to recognize that both the accurate and inaccurate visual-schematic representation category represent a mixture of internal visualization (mental imagery) and external visualization (gestures, drawing) efforts. Although these different approaches seem to share a common processing mechanism (Leutner, Leopold, & Sumfleth, 2009; Schnotz & Kürschner, 2008), there may also be differences. For example, mental imagery requires participants to keep