Learning and Instruction 31 (2014) 33–45

Contents lists available at ScienceDirect

Learning and Instruction

journal homepage: www.elsevier.com/locate/learninstruc

The role of dynamic spatial ability in geoscience text comprehension

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ARTICLE INFO

Article history:
Received 15 April 2013
Received in revised form
27 December 2013
Accepted 28 December 2013

Keywords:
Spatial ability
Geoscience learning
Individual differences

ABSTRACT

The current experiment investigated the effects of a dynamic spatial ability on comprehension of a geoscience text on plate tectonics and the causes of volcanic activity. 162 undergraduates (54% female) from a large public university who had little prior knowledge of this science content area were asked to learn about plate tectonics. Measures of spatial ability and working memory capacity were used to predict comprehension from a text that contained either no images, static images, or animated versions of the static images. Only the dynamic spatial ability measure interacted with the type of illustrations contained in the text, and was shown to be especially relevant for comprehension when readers did not receive animations. These results demonstrate a novel influence of individual differences in dynamic spatial ability on comprehension of text describing dynamic spatial phenomena.

1. Introduction

Learning from expository science texts, like all comprehension processes, requires that readers go beyond a verbatim memory trace to construct an understanding of what the text is really about (Kintsch, 1994). Particularly when texts describe how or why scientific processes or phenomena occur, the goal for comprehension can be seen as the development of a situation model, causal model, or runnable mental model of the content (Gentner & Stevens, 1983; Graesser & Bertus, 1998; Johnson-Laird, 1983; Kintsch, 1998; Trabasso & van den Broek, 1985; Wiley & Myers, 2003; Zwaan & Radvansky, 1998). Further, many topics in science involve understanding phenomena with elements that move and interact across time and space. Understanding how these elements move, interact, and change over time may be more amenable to spatially-based mental representations, and may not be easily translated into verbal propositions (Friedman & Miyake, 2000; Hegarty, 1992; Hegarty, Canham, & Fabrikant, 2010; Rinck, 2005). For example, for learners to successfully understand the geological phenomena of plate tectonics, they must first identify the relevant conceptual units (e.g., plates, magma, plate boundaries, etc.), which itself is often difficult for learners (Kortz et al., 2011). Learners must then consider how these conceptual units interact and change over time, and thus they need to represent this dynamic spatial information in their own mental models of the tectonic system (Gentner & Stevens, 1983; Hegarty, 1992). This suggests that one constraint on science text comprehension may be individual differences in visuospatial skills, because they may be especially relevant for the creation of spatial situation models (Friedman & Miyake, 2000; Haenggi, Kintsch, & Gernsbacher, 1995).

1.1. Individual differences in visuospatial ability

A long tradition of factor-analytic research has provided strong evidence that 'visuospatial ability' can not only be differentiated from general intelligence and verbal ability, but also represents a complex of multiple, distinguishable, visuospatial faculties (see Hegarty & Waller, 2005, for a comprehensive review). One traditional taxonomic distinction differentiates visuospatial abilities (and the tests that measure them) into two main classes: those that tap the ability to rotate objects in space (e.g., block and figure rotation tasks) and those that tap the ability to visualize or reconceptualize an existing spatial representation into a revised new whole (e.g., paper folding, form board; Carroll, 1993; Cooper, 1975; Cooper & Shepard, 1973; Mumaw, Pellegrino, Kail, & Carter, 1984; Pellegrino & Hunt, 1991). These two sub-types of spatial ability, although generally recognized as separate abilities (Miyake, Friedman, Rettinger, Shah, & Hegarty, 2001), are usually highly correlated and can sometimes be difficult to differentiate (Carroll, 1993; Just & Carpenter, 1985; Stumpf & Eliot, 1995). Hunt, Pellegrino, and their colleagues also classify both of these types of abilities within a single category that they refer to as static spatial ability (Fischer, Hickey, Pellegrino, & Law, 1994; Hunt, Pellegrino, Frick, Farr, & Alderton, 1988; Law, Pellegrino, & Hunt, 1993). They emphasize that these measures deal with transformation of a single

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0959-4752/$ – see front matter
http://dx.doi.org/10.1016/j.learninstruc.2013.12.007

object and not the interaction of multiple objects over space and time. Another recent theoretical framework classifies both of these tasks into what is known as the *intrinsic-dynamic* category, which represents the transformation of spatial coding within objects relative to starting and end points (Newcombe & Shipley, 2012; Uttal et al., 2013). Although this new label includes the word 'dynamic', again the emphasis here is on within-object manipulations.

Importantly, individual differences in performance on these types of within-object-manipulation visuospatial tasks (both rotation and visualization) have been shown to explain unique variance in visuospatial memory performance over and above working memory capacity (Miyake et al., 2001) and other general reasoning/problem solving abilities (Hegarty & Waller, 2005). These individual differences in visuospatial ability have also been shown to positively predict performance on tasks that require explicit visuospatial information processing, such as using visualizations to reason mechanically about physical objects like integrated gears or pulley systems (Boucheix & Schneider, 2009; Hegarty & Sims, 1994; Hegarty & Steinhoff, 1997), learning a new route from a map (Sanchez & Branaghan, 2009), or learning how technologies such as bicycle pumps or surfactants work from diagrams (Höffler & Leutner, 2011; Mayer & Sims, 1994). A recent meta-analysis by Höffler (2010) has corroborated that visuospatial abilities produce a general learning benefit when learners engage in processing of visuospatial information. Individual differences in within-object manipulation abilities have also been found to predict the comprehension of narrative texts where readers follow the actions of a character in physical space (Bower & Morrow, 1990; De Beni, Pazzaglia, Gyselinck, & Meneghetti, 2005; Fincher-Kiefer, 2001; Fincher-Kiefer & D'Agostino, 2004; Haenggi et al., 1995; Meneghetti, De Beni, Pazzaglia, & Gyselinck, 2011). Thus, within-object manipulation spatial abilities (WOMSA) seem especially relevant for visuospatial processing and the development of representations which contain visuospatial information.

1.2. Visuospatial abilities and science

Although many have posited that visuospatial abilities are key for understanding in science (Halpern et al., 2007; Wu & Shah, 2004), there is little direct evidence supporting this connection. It has been noted that some of the greatest theoretical discoveries in science such as the double helix, fluid dynamics, quantum mechanics, and theories of plate tectonics, have all been attributed to the ability of great individuals to think spatially (NRC, 2006). However, the evidence for the link between visuospatial ability and performance in science is largely anecdotal (such as these examples), or instead based on observational or correlational evidence such as scientists and students in advanced science courses testing better on measures of within-object visuospatial abilities than the normal population (Self & Golledge, 1994; Wu & Shah, 2004). What has been fairly well documented are the selection factors that operate as individuals make career choices, with less-visuospatially-able students typically choosing to take fewer science, math and engineering courses (Halpern et al., 2007; Shea, Lubinski, & Benbow, 2001).

There are a handful of studies that have found correlations between classroom exam performance and within-object visuospatial abilities in such topics as organic chemistry (Bodner & McMillen, 1986; Carter, LaRussa, & Bodner, 1987; Pribyl & Bodner, 1987; Wu & Shah, 2004) and earth science (Black, 2005; Sibley, 2005). However, these correlational studies fail to rule out general individual differences in ability or even prior knowledge as causal factors. Further, there are also examples of within-object visuospatial ability failing to predict learning of science content, including in biology (Koroghlanian & Klein, 2004) and physics (ChanLin, 2000). As a result, more direct investigations of the relation between spatial abilities and science learning are needed. This prompts the question as to whether or not the traditional measures of within object visuospatial abilities are indeed the most relevant for the kinds of representations that are needed for comprehension of some scientific topics. It is possible that the simple visualization and manipulation of spatial information captured by these tasks is not necessarily relevant for all kinds of complex science reasoning occurring in these domains. Given that many scientific phenomena reflect the combination or relation of multiple objects or elements over time and space, perhaps a visuospatial ability which better captures this might be a better predictor of comprehension.

A distinct ability that might better predict comprehension in this content area of science is the construct of *multiple-object dynamic spatial ability* (MODSA) which deals with the tracking of spatial information of multiple objects across space *and* time. This construct was introduced by Hunt, Pellegrino and their colleagues approximately two decades ago (Fischer et al., 1994; Hunt et al., 1988; Law et al., 1993). In tasks that measure MODSA, subjects are asked to predict not only where multiple moving objects will intercept, but also to make judgments as to when this interception might occur. Thus, integral to performing a MODSA task is the ability to represent time and use this information to calculate relative velocity, which is then used to extrapolate a viable intercept, and to make an appropriate spatial judgment (Hunt et al., 1988). Consequently, the primary relationships being processed are spatial orientations and relations over time that are updated continuously, rather than isolated judgments of relations between features within a single object.

Consistent with this theoretical classification, Hunt, Pellegrino and colleagues originally proposed MODSA as an ability that is independent from performance on single-object manipulation tasks discussed above, as well as independent from perspective taking on tasks like the Guilford–Zimmerman, and they confirmed this with several factor analyses (Hunt et al., 1988). This has been corroborated more recently by two subsequent studies which indeed found MODSA to be an independent and significant predictor of complex spatial–temporal performance, explaining performance over and above the contributions of WOMSA measured by several common tests of spatial relations and visualization (Contreras, Colom, Hernandez, & Santacreu, 2003; D'Oliveira, 2004). It is important to note, however, that tasks designed to measure MODSA and WOMSA involve the manipulation of spatial information, so naturally these measures share a modest correlation (approximately .20–.30, Contreras et al., 2003; D'Oliveira, 2004; Hunt et al., 1988).

The relationship between MODSA and other critical cognitive abilities such as working memory capacity is less clear. MODSA has been found to explain unique variance over and above verbal intelligence on performance on IQ tests (Jackson, Vernon, & Jackson, 1993) and also appears to vary independently from education level (Contreras, Colom, Shih, Alava, & Santacreu, 2001). Working memory capacity has also been implicated in performance in several spatial reasoning and intelligence tasks (Kane et al., 2004; Miyake et al., 2001), and spatial memory/manipulation tasks (Duff & Logie, 1999; Hegarty & Steinhoff, 1997; Pearson, Logie, & Gilhooly, 1999). This suggests that these constructs could potentially share variance with one another given their similar patterns of prediction. Further, it has also been shown recently that working memory may mediate the relationship between some spatial abilities and the recall of spatial texts (Meneghetti et al., 2011). Similarly, concurrent visuospatial tasks can disrupt the consolidation of information in verbal working memory (Gyselinck, Jamet, & Dubois, 2008), and similarly, verbal concurrent tasks can negatively