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The role of working memory in the association between number magnitude and space

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Abstract

In two experiments, participants performed a magnitude comparison task in single and dual-task conditions. In the dual conditions, the comparison task was accomplished while phonological or visuospatial information had to be maintained for a later recall test. The results showed that the requirement of maintaining visuospatial information produced the lack of spatial-numerical association of response codes (SNARC) effect. The SNARC effect was not found even when the performance in the comparison task did not decline, as indicated by a similar distance effect in all conditions. These results show a special role for the visuospatial component of working memory in the processing of spatial representation of numbers and an interesting dissociation between SNARC and distance effects.

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1. Introduction

A general view in number processing research is that numerical magnitude is analogically represented. The representation is organized by numerical proximity with increasing fuzziness for larger numbers (Dehaene, 1992; Gallistel & Gelman, 1992; Moyer & Landauer, 1967). Among different theories of analogical representation, an influential model is the *mental number line* (Dehaene, 1992). It could be conceptualized as a set of units over which different magnitudes produce the activation of a sub-set of units and where close numbers are represented with overlapping distributions of activation. This model is able to account for some findings in number processing that are very similar to those observed in psychophysic studies, such as the *distance effect* (Moyer & Landauer, 1967): the response time to compare two numbers is an inverse function of the numerical distance between them. Several process-oriented models have been proposed to explain how different magnitudes are coded as space-related representation along this hypothetical number line (for a comparison among concrete proposals see Verguts, Fias, & Stevens, 2005).

In addition, the mental number line is assumed to be spatially oriented from left-to-right, which might account for the findings about a relationship between numbers and spatial information. The more examined finding has been the so-called Spatial-Numerical Association of Response Codes (SNARC) effect (Dehaene, Bossini, & Giraux, 1993). It consists of an association between the relative numerical magnitude and the response side, such that larger numbers are associated with right side and smaller numbers with left side (for a review see Fias & Fischer,

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2005). Recent behavioral and electrophysiological evidence indicates that SNARC effect is solved at a selection response stage (e.g., Gevers, Caessens, & Fias, 2005; Gevers, Ratinckx, De Baene, & Fias, 2006; Gevers, Verguts, Reynvoet, Caessens, & Fias, 2006; Keus & Schwarz, 2005). Gevers, Lammertyn, Notebaert, Verguts, and Fias (2006) suggested a computational model in which similar to other conflict tasks, SNARC effect could be explained in terms of a dual-route architecture, where the numerical stimulus produces an activation of a common spatial response code from independent sources. On the one hand, a spatial code associated with the numerical magnitude activates the response code (unconditional route, independent of instructions). On the other hand, the response code is also activated by the response defined by the task instructions (conditional route). When both sources activate the same response code, decisions are faster because the threshold response at the selection stage is reached faster. However, when both sources activate different response codes, the selection stage takes more time to reach the threshold and thus, responses are slower.

More interesting for the present work is that the number-spatial relationship is quite flexible. It does not depend on the absolute magnitude of the numbers, but on the relative magnitude within the tested interval (Dehaene et al., 1993; Fias, Brysbaert, Geypens, & d'Ydewalle, 1996). The left-to-right orientation seems to be related to cultural habits, as much as a reverted SNARC effect is observed for individuals with right–left writing systems (e.g., Dehaene et al., 1993; Zebian, 2005). But, even short-term inversion of SNARC effect has been observed when subjects are primed with clock-faces (Bächtold, Bumüller, & Brugger, 1998), which indicates that the space-number association is context dependent. Therefore, although the activation of numerical magnitude is closely related to spatial properties, the relation between numerical processing and spatial properties can be modified by the task goal. The retrieval of information when performing a task and its modulation by current goals directly suggest the involvement of working memory.

Working memory is defined as a memory system that keeps active a limited amount of information for a brief period of time (e.g., Baddeley & Hitch, 1974). Although there is not a general agreement about an exact conceptualization of working memory (see Miyake & Shah, 1999), one of the most influential theories (Baddeley, 1986; Baddeley, 1996) proposes that it is composed of a central executive and phonological and visual subsystems. The central executive is considered responsible for the control and regulation of cognitive processes. It coordinates the activities of the other two more specialized components. The phonological component, known as *phonological loop*, is involved in temporarily storing of verbal information and its maintenance by active rehearsal processes (e.g., Baddeley, Lewis, & Vallar, 1984). The visuospatial component, the so-called *visuospatial sketchpad*, is used for storing and manipulating visual and spatial material (e.g., Della Sala, Gray, Baddeley, Allamano, & Wilson, 1999).

The flexibility of SNARC effect suggests that spatial properties associated to numerical information are temporary represented in visuospatial working memory when participants perform a numerical task (i.e., number comparison task). This temporal representation is dependent on the task demands and so, the observed effect on subjects' performance (i.e., SNARC effect) varies with the numerical range and context.

A frequently used approach to study the role of the working memory components when performing a given task is the dual-task paradigm. The rationale is to determine whether the task of interest is disrupted by the concurrent performance of a secondary task that has been empirically probed to place heavy load on the individual components of working memory. From our suggestion, a straight prediction is that the activation of spatial properties of numbers will be interfered by a secondary task tapping the visuospatial component of working memory.

In the next two experiments, we evaluated the relation between number magnitude and space under two different load conditions: Visuospatial load and phonological load. The main task used was a comparison task, in which participants indicated if a number was larger or smaller than the standard (i.e., 5). The performance in a single comparison task was compared to a dual-task setting in which participants performed the comparison task while they retained a phonological load (i.e., consonant-vowel-consonant, CVC non-words; e.g., Trbovich & LeFevre, 2003) or a visuospatial load (i.e., a computerized version of the Corsi Block task, e.g., Berch, Krikorian, & Huha, 1998). The effect of the load condition on the association between numerical processing and space was examined by comparing the distance and SNARC effects in the three conditions (i.e., single, phonological load and visuospatial load).

We suggest that spatial properties associated to numerical information are temporarily represented in visuospatial working memory. These spatial properties are responsible for the SNARC effect, but they are not required for performing the relevant task (i.e., magnitude comparison). Therefore, representation of these spatial attributes would be hard in situations of visuospatial overload and, consequently, the SNARC effect might not be observed. Following our suggestions, the phonological load should not affect a temporary visuospatial representation, and so, the SNARC effect should not be affected. Nevertheless, even when phonological load does not involve the visuospatial working memory, it represents a situation of higher load in cognitive control functions. In these situations, it has been shown that the processing of irrelevant information may be increased (e.g., Lavie, Hirst, Fockert, & Viding, 2004). Hence, the SNARC effect could increase in phonological load condition.

2. Experiment 1

The aim of this experiment was to evaluate the role of visuospatial working memory and phonological working