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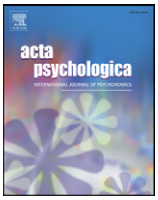

The link between mental rotation ability and basic numerical representations

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ABSTRACT

Mental rotation and number representation have both been studied widely, but although mental rotation has been linked to higher-level mathematical skills, to date it has not been shown whether mental rotation ability is linked to the most basic mental representation and processing of numbers. To investigate the possible connection between mental rotation abilities and numerical representation, 43 participants completed four tasks: 1) a standard pen-and-paper mental rotation task; 2) a multi-digit number magnitude comparison task assessing the compatibility effect, which indicates separate processing of decade and unit digits; 3) a number-line mapping task, which measures precision of number magnitude representation; and 4) a random number generation task, which yields measures both of executive control and of spatial number representations. Results show that mental rotation ability correlated significantly with both size of the compatibility effect and with number mapping accuracy, but not with any measures from the random number generation task. Together, these results suggest that higher mental rotation abilities are linked to more developed number representation, and also provide further evidence for the connection between spatial and numerical abilities.

1. Introduction

A strong connection has long been noted between mathematical and spatial cognitive abilities. Studies of developmental, individual, and sex differences among cognitive skills have consistently shown that spatial aptitude and mathematical aptitude tend to align (Geary, Saults, Liu, & Hoard, 2000; Reuhkala, 2001). However, it is unclear whether this connection exists solely with high-level mathematical abilities or if it is founded upon a deeper overlap between spatial abilities and basic numerical cognition. Most of the current evidence has established connections between spatial abilities and high-level numerical abilities, such as mathematical abilities (e.g., Dumontheil & Klingberg, 2012). However, it is possible that such connections are based on a more fundamental link between spatial abilities and basic numerical abilities that serve as the building block for high level numerical abilities (Butterworth, 2010). Despite the common intuition that numbers are represented purely abstractly (for a review see Cohen Kadosh & Walsh, 2009), numerical cognition has been shown to incorporate a vigorous spatial component; for instance, spatial influences have been shown on numerical tasks such as number interval bisection, parity judgment, and numerical value comparison, whereas irrelevant but automatically-processed numbers have been shown to influence spatial tasks such as attentional cueing and physical line bisection (e.g., de Hevia, Vallar, & Girelli, 2008; Vallar & Girelli, 2009). Space is a powerful conceptual framework for learning number properties of ordering and magnitude, as illustrated in the embodied cognition account of Lakoff and Nunez (2000), and as evidenced in the widespread use of spatial number lines in early mathematics education (Ernest, 1985). Additionally, lesion and imaging studies have implicated common areas in the parietal cortex for both spatial (e.g., physical line bisection, spatial attention and orientation) and numerical (e.g., number comparison, numerosity and magnitude judgment) abilities, suggesting that they may recruit shared neural circuits (for reviews see Cantlon, Platt, & Brannon, 2009; Cohen Kadosh, Lammertyn, & Izard, 2008; Hubbard, Piazza, Pinel, & Dehaene, 2005; Walsh, 2003). It follows, then, that spatial and numerical cognitive abilities may indeed be closely linked in the nature of their representation.

1.1. Mental rotation

Mental rotation has proven to be a robust and popular measure of spatial ability, particularly for spatial representation and mental manipulation of objects (Borst, Kievit, Thompson, & Kosslyn, 2011; Poltrock & Brown, 1984). Mental rotation is a computationally complex spatial

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process, with performance varying widely across individuals irrespective of other intelligence measures (Borst et al., 2011; Johnson & Bouchard, 2005; Shepard & Metzler, 1971). Opinions have varied as to how mental rotation fits within the subset of observable spatial skills, and how these skills ought to be grouped or classified in terms of mental processes (for instance, see Voyer, Voyer, & Bryden, 1995). Despite this disagreement, mental rotation has nonetheless been shown to correlate with other tests of spatial abilities, such as mental paper-folding tasks, space relations tests, and spatial working memory (Just & Carpenter, 1985; Kaufman, 2007; Reuhkala, 2001), suggesting that it may predict, at least to some degree, more general spatial skills of a participant. This extrapolation to other spatial abilities may occur in the form of spatial object mapping; according to converging neuroimaging evidence, mental rotation appears to recruit posterior parietal areas implicated in spatially-mapped analog representations (for a review see Zacks, 2008). Both behavioral and imaging evidence suggest that mental rotation tasks evoke visuospatial representations corresponding to object rotation as seen in the physical world, through graded transformational processes working upon analog object representations. For instance, Shepard and Metzler (1971) demonstrated that response latencies in a mental rotation task varied as a linear function of rotational angle between the target and comparison object. Furthermore, several fMRI studies have since found neural correlates for this behavioral effect, showing that bilateral parietal lobe activation increases as a function of rotational angle in mental rotation of objects, both when visually presented (Carpenter, Just, Keller, Eddy, & Thulborn, 1999; Gogos et al., 2010) and when retrieved from memory (Just, Carpenter, Maguire, Diwadkar, & McMains, 2001).

1.2. Number representation

Like mental rotation, basic number representation has been widely investigated. By "number representation" or "numerical representation" we simply mean the mental organization and framework within which information about the cognitive concept of numbers is stored. Thus number representation is the most basic level of numerical cognition upon which all other (more complex) numerical and mathematical thinking builds. While this basic number representation must ultimately have a neuronal basis, it is important to remember that representation and neuronal organization are not necessarily the same thing, and that a particular proposed system of number representation could have many possible neuronal manifestations. In this article it is equally important to distinguish what we will refer to as "number processing": the nature of processing necessarily relies upon the underlying representation of the concepts and percepts being acted upon, but it is not a synonym for representation. Rather, it refers to the *act of engaging* mental representations, in order to use this numerical information for number-related tasks or other cognitive processes. Therefore, since number representation is not accessible by any means other than number processing, observation of number processing is the only way to infer aspects of the underlying representation.

It is similarly worthwhile to explain here the distinction between, on the one hand, *numerical* skills, abilities, or processing, and on the other hand, *mathematical* skills, abilities, or processing. The relationship between these two concepts is a nested one; numerical skill is only one component part of mathematical skill. In this model, numerical skills necessarily rely heavily—perhaps primarily—upon numerical representation, with few other basic sub-processes mediating their outcomes, such as visual recognition of numerals. On the other hand, mathematical skills additionally rely upon (and therefore can be amplified or attenuated by) a greater number, degree, and complexity of sub-skills and sub-processes, such as logical inference, memorization of calculation procedures, working memory, etc. For instance, factors such as working memory have been shown to predict later mathematical performance in a longitudinal developmental study (Moeller, Pixner, Zuber, Kaufmann, & Nuerk, 2011). Thus, to investigate numerical representation we utilized tasks that engage numerical, rather than mathematical, skills, as mathematical measures may be affected by a multitude of these non-numerical factors.

Details of number representation have been inferred from several types of tasks, including number line mapping and numerical comparisons. Numerical comparison tasks ask participants to indicate which of the two numbers is larger in magnitude (or sometimes, smaller in magnitude). This requires participants to access mental representations of the numerical magnitude of each number, and to perform comparative processes on these representations. Such tasks show several reliable behavioral effects, each shedding light on the inner workings of number processing and underlying representation. One of the effects, the unit-decade compatibility effect, arises from the decimal place-value structure of symbolic Arabic numbers. It provides evidence for decomposed processing of multi-digit numbers, thereby challenging a previous suggestion that numbers are represented by a single holistic representation, i.e., as an integrated entity which does not retain place-value information (Dehaene, Dupoux, & Mehler, 1990). The compatibility effect reflects a performance cost for trials in which the magnitude decision between unit digits of the two numbers is incompatible with (that is, opposite to) the magnitude decision between the decade digits (e.g., for a 'compatible' trial, such as 42 vs. 57, $4 < 5$ and $2 < 7$; but for an 'incompatible' trial, such as 37 vs. 52, $3 < 5$ but $7 > 2$; Nuerk, Weger, & Willmes, 2001). The performance cost for incompatible trials suggests that the unit digits of two-digit numbers are automatically processed, even when they are irrelevant to the task.

Further evidence using eye-tracking supports this interpretation, indicating that participants showed more eye fixations on unit digits than decade digits, and especially so for incompatible trials (Moeller, Fischer, Nuerk, & Willmes, 2009). This pattern has been interpreted as reflecting the need to inhibit magnitudes of unit digits for incompatible trials only, as the (irrelevant) unit comparison interferes with the decade and overall comparison; therefore the data are most consistent with a model in which both digits are processed separately (see Moeller, Fischer, et al., 2009, for a detailed version of that argument including hypothetical eye fixation patterns for various models and conditions). Such separate processing requires the activation of multiple representations, at least one for each digit. Thus the compatibility effect can serve as a quantifiable measure indicating the robustness of simultaneous processing of multiple (i.e., decomposed-digit) numerical representations (for a review, see Nuerk, Moeller, Klein, Willmes, & Fischer, 2011). This would seem to indicate that larger compatibility effects would accompany a more complex, advanced system of number representation; indeed, developmental studies of the compatibility effect have shown it to increase with age and numerical experience (Mann, Moeller, Pixner, Kaufmann, & Nuerk, 2011) and to predict later arithmetic ability (Moeller et al., 2011).

Another type of numerical task, the number line mapping task (also termed number line estimation task), has been widely utilized in the last decade as a measure of internal spatial representations of number in both children and adults (Cohen Kadosh, Soskic, Iuculano, Kanai, & Walsh, 2010; Karolis, Iuculano, & Butterworth, 2011; Siegler & Opfer, 2003). In its commonly used number-to-space version, the paradigm typically presents participants with a horizontal line segment labeled with a numerical value at either end (usually 0 at the left, and 10, 100, or 1000 at the right), and asks them to mark the place at which a target number should be located on the line. The deviation of this mark from the true position of the number on a linear equidistance line is assessed, and both absolute deviations as well as the form of these deviations are modeled to explore the possible underlying magnitude representation (see Moeller, Pixner, Kaufmann, & Nuerk, 2009; Siegler & Opfer, 2003; Slusser, Santiago, & Barth, 2012 for different suggestions). Developmental studies show that children's mean absolute error percentages on number line tasks drop below a threshold of 10% by age 8 for numbers 0–100, and by age 10 for numbers 0–1000, and that performance in this task predicts later arithmetic learning (Booth & Siegler, 2006,