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Spontaneous mapping of number and space in adults and young children

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ABSTRACT

Mature representations of space and number are connected to one another in ways suggestive of a 'mental number line', but this mapping could either be a cultural construction or a reflection of a more fundamental link between the domains of number and geometry. Using a manual bisection paradigm, we tested for number line representations in adults, young school children, and preschool children. Non-symbolic numerical displays systematically distorted localization of the midpoint of a horizontal line at all three ages. Numerical and spatial representations therefore are linked prior to the onset of formal instruction, in a manner that suggests a privileged relation between spatial and numerical cognition.

1. Introduction

Some of the central achievements of formal mathematics depend on the mapping between number and space (e.g., Descartes, 1637/2001; Euclid (in Heath, 1956)). Fundamental to this mapping, and to measurement, is the arrangement of numbers on a line. Is the number line a product of human invention and cultural innovation, or does it spring from a basic propensity of the human mind to link representations of space and number? We explore this issue through studies of adults and children.

The best evidence for mental number lines comes from studies of the impact of spatial information on adults' numerical processing. When adults identify or compare numbers, they automatically activate an internal representation of a directional spatial continuum (Dehaene, 1992). In most literate adults, this representation yields a temporal advantage in responding to smaller numbers on the left and to larger numbers on the right (the "SNARC effect": Dehaene, Bossini, & Giraux, 1993; Fias, 2001; Fias, Brysbaert, Geypens, & d'Ydewalle, 1996). The implicit association of a number with a lateralized spatial code also modulates performance in visuo-spatial tasks: appropriately positioned numbers speed the detection of lateralized targets and the initiation of motor movements towards the left or right spatial hemifields (Fischer, 2003; Fischer, Castel, Dodd, & Pratt, 2003).

Finally, neurological patients with left hemifield neglect show a common signature bias both in bisecting a line and in bisecting a numerical interval, overestimating the midpoint number consistently with a rightward bias on a mental number line (Zorzi, Priftis, & Umiltà, 2002; see also Rossetti et al., 2004; Vuilleumier, Ortigue, & Brugger, 2004). Nevertheless, it has been argued that the association between number and spatial laterality is related specifically to the ordinal meaning of numbers (Gevers, Reynvoet, & Fias, 2003, 2004), and is modulated by visual scanning habits related to reading (Dehaene et al., 1993; Zebian, 2005, but c.f. Bächtold, Baumüller, & Brugger, 1998; Ito & Hatta, 2004).

Further evidence for a number–space interaction comes from experiments using a different type of line bisection task. In this task, subjects are presented with horizontal lines flanked by Arabic digits, and they indicate the subjective midpoint of each line. Although the flanking numbers are irrelevant to the task, adults show a spatial bias towards the larger number, irrespective of its lateral position (de Hevia, Girelli, & Vallar, 2006; Fischer, 2001). This phenomenon is thought to reflect a cognitive illusion of length

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brought about by numerical information: a relative expansion of the lateral extent ipsilateral to the larger number (de Hevia, Girelli, Bricolo, & Vallar, 2008; de Hevia et al., 2006). It suggests that representations of length and numerosity are mapped onto an integrated representation of magnitude (Moyer & Landauer, 1967).

What is the source of this mapping? Because all of the above findings were obtained with adults, they could come about in two different ways. First, space and number may be intrinsically related by a common mental metric (e.g., Dehaene, 1997; Gallistel & Gelman, 2000; Walsh, 2003). Alternatively, human adults may come to internalize a linear representation of number because of their extensive exposure to external spatial representations of number, over the course of mathematics instruction and everyday experience. Number lines are introduced to children at the start of school: they are instantiated on rulers, tape measures, thermometers, and other measuring devices. Children and adults, therefore, may learn the mapping of number to space.

Considerable research is consistent with the latter possibility. For example, the tendency to process large numbers more efficiently on the right and small numbers on the left, as indexed by the SNARC effect, emerges over the course of the elementary school years (Berch, Foley, Hill, & Ryan, 1999; van Galen & Reitsma, 2008; see also Bachot, Gevers, Fias, & Roeyers, 2005), and is reversed in school children learning to read from right to left (Zebian, 2005). Recent research suggests that the directional mapping of numbers onto space is not entirely triggered by reading performance, since preliterate children display an intuition for the left-to-right organization of numerical magnitude, which the authors identify as deriving from experience in counting (Opfer & Thompson, 2006). Finally, the internal organization of numerical magnitude at different ages is explicitly represented through space in the 'number line task', where subjects are asked to place numerical values in a horizontal line (Siegler & Opfer, 2003). Through this task, it has been revealed that younger children and uneducated adults have logarithmic representations of magnitude, in contrast to a more mature, linear pattern of numerical representation, which is achieved across the school years through adulthood (Dehaene, Izard, Spelke, & Pica, 2008; Siegler & Opfer, 2003).

These findings suggest that aspects of the spatial representation of number are influenced by experience, culture or instruction, but they do not reveal whether humans have an unlearned, automatic, and non-directional mapping of number to space. First, the numerical information in the above experiments was presented in the form of Arabic digits: a symbolic system that must be learned and that may not have been fully mastered by the youngest children. Second, the spatial/numerical mapping tested in the above experiments is directional: a mapping of larger numbers to the right or left side of space. A basic mapping of space to number may exist, but its direction may be fixed by experience. And third, the above experiments required an explicit processing of the numerical information, e.g., by asking children to place each number on a line (Siegler & Opfer, 2003), or using a parity judgment task (Berch et al., 1999). An automatic, spontaneous interaction between number and space is best probed in a task in which number is irrelevant.

The present experiments investigate these possibilities. We employed the non-directional line bisection task, in which participants indicate the midpoint of a line that is flanked by two numbers of unequal values. In the critical test conditions, we presented the flanking numbers not symbolically, as Arabic digits, but non-symbolically, as arrays of dots. Moreover, in the line bisection numbers are irrelevant to the task. On each trial, adults, school children, or preschool children were presented with a line flanked by two dot arrays differing in numerosity, and they were asked to indicate the midpoint of the line. If number and space are spontaneously related by an abstract and privileged mapping, then adults and children should show a similar bias in their line bisection, choosing as the midpoint a location that is closer to the larger numerosity.

2. Experiment 1

The first experiment investigated whether non-symbolic numerical displays cause the same distortion of adults' line bisection as symbolic numerical displays. On half the trials, adults indicated the midpoint of a line flanked by two Arabic digits, as in past research (de Hevia et al., 2006); on the remaining trials, adults indicated the midpoint of a line flanked by two arrays of dots, matched in numerosity to the digits. If the effects of number on performance in the line bisection task are related to an abstract representation of quantity, and not to a more specific familiarity with Arabic digits arranged in a line, then the same effects should be obtained with symbolic and non-symbolic quantities.

2.1. Method

2.1.1. Participants

The participants were 19 adult subjects (8 male; mean age: 25 years), drawn from lists of volunteers in the Psychology Department Study Pool. All participants were right-handed and had normal or corrected-to-normal vision. Informed consent was obtained from participants prior to the study, and the numerical bias was explained at the end of the experiment.

2.1.2. Materials

On each trial, a horizontal black line, 1 mm in width and either 60 or 80 mm in length, was presented in the centre of a horizontally oriented sheet (216 mm wide and 279 mm high). On symbolic number trials, the Arabic numerals '2' and '9', each 4 mm wide and 6 mm high, appeared 1 mm to the left and right of the line. On non-symbolic trials, the total area occupied by the dots in each array was equal: each dot in the 2-dot array had a 10 mm diameter, occupying an area of 78.5 mm^2 each; each dot in the 9-dot array had a 4.71 mm diameter, occupying an area of 17.45 mm^2 each. Each array of dots occupied a virtual, not visible circle (30 mm diameter) placed 2 mm apart from the line. Six different arrays of dots were generated in an effort to control and test for configural effects on line bisection (Fig. 1).