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Spatial-numerical consistency impacts on preschoolers' numerical representation: Children can count on both peripersonal and personal space

Luca Rinaldi[a,b,*], Marcello Gallucci[a,b], Luisa Girelli[a,b]

[a] Department of Psychology, University of Milano-Bicocca, Milano, Italy
[b] NeuroMI, Milan Center for Neuroscience, Milano, Italy

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ABSTRACT

Although the existence of an association between numbers and space has been largely documented in educated adults, the origin of this association still remains debated. Recent evidence suggests that associations between numbers and space might originate during the preschool years from the repeated action of counting in peripersonal space. However, it is also possible that preschoolers may additionally acquire directional preferences by counting on their own body, specifically on their fingers. To address this hypothesis, the present study explores the presence of early directional indexes in processing numerical information in both peripersonal and personal space in a sample of 90 preschoolers. We identified children who consistently exhibited a counting directional bias and generalized it to their processing of numbers in space. Moreover, given the tight connection between counting routine and numerical knowledge, we investigated the relation between these indexes and numerical achievement, evaluated by means of various tasks. Results indicate that distinct spatial-numerical associations, in both peripersonal and personal space, coexist from an early age and can be used flexibly. However, regardless of its directionality, the presence of a consistent spatial-numerical association appears to be related to numerical comprehension.

1. Introduction

The tendency to associate numerical information with spatial coding can be observed at various stages of life (de Hevia, Girelli, & Macchi Cassia, 2012), and it is corroborated in adults by behavioral, neuropsychological and neuroanatomical data (for a review, see de Hevia, Vallar, & Girelli, 2008). An exploited piece of evidence of number-space mapping is found in speeded classification tasks, in which smaller numbers elicit consistently faster left-sided responses and larger numbers faster right-sided responses (Dehaene, Bossini, & Giraux, 1993). This well-documented compatibility effect, named the 'SNARC' effect (Spatial Numerical Association of Response Codes; Dehaene et al., 1993), adds to other empirical evidence supporting the hypothesis that numerical information is spatially coded into a left-to-right oriented 'mental number line' (Dehaene, 1992; for a review, see de Hevia et al., 2008). Critically, the internal direction of the 'mental number line' seems to be modulated by cultural factors, because readers of right-to-left languages frequently show reduced or opposite spatial-

* Corresponding author at: Dipartimento di Psicologia, Università degli Studi di Milano-Bicocca, Piazza dell'Ateneo Nuovo 1, Edificio U6, 20126 Milano.
E-mail address: l.rinaldi2@campus.unimib.it (L. Rinaldi).

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numerical associations (SNAs) compared to individuals from Western cultures (Shaki, Fischer, & Göbel, 2012; Shaki, Fischer, & Petrusic, 2009). Accordingly, the SNARC effect has been proposed to originate from exposure to formal education, in which learning of reading and writing might induce critical directional scanning practices at the origin of number-space coding (Berch, Foley, Hill, & Ryan, 1999).

During the last decade, however, several studies have challenged this view. First, evidence from preverbal infants (Bulf, de Hevia, & Macchi Cassia, 2015; de Hevia, Girelli, Addabbo & Macchi Cassia, 2014; Macchi Cassia, Picozzi, Girelli, & de Hevia, 2012) and non-human animals (Rugani, Kelly, Szelest, Regolin, & Vallortigara, 2010; Rugani, Vallortigara, Priftis & Regolin, 2015) support the idea that number-space mapping emerges spontaneously and very early in life, rather than after learning formal practices associated with enculturation. These findings indicate that SNAs might constitute a common trait of human and, possibly, non-human cognition.

Second, enculturation begins before schooling (for a review, see McCrink & Opfer, 2014). We are surrounded by cultural determinants beginning approximately at birth: observational routines such as watching parents or caregivers while ordering elements in the space around us play a critical role in establishing SNAs (for a discussion, see Nuerk et al., 2015). It might be possible that visual scanning habits may consolidate by observational learning, partially contributing to the early spatial coding of numerical information and, therefore, leading to a left/small and right/large preferred mapping in western cultures (Opfer, Thompson, & Furlong, 2010). Specifically, Opfer et al. (2010) suggested that SNAs might be consolidated through the physical action of counting in peripersonal space, a routine that children often adopt to enumerate sets of objects. Accordingly, preschool evidence of number-space mapping has been repeatedly reported in recent years (Hoffmann, Hornung, Martin, & Schiltz, 2013; McCrink, Shaki & Berkowitz, 2014; Opfer & Furlong, 2011; Patro, Fischer, Nuerk & Cress, 2015; Patro & Haman, 2012; Shaki et al., 2012). Critically, the presence of number-space mapping at this age seems to have an important representational function, favoring numerical achievement. Indeed, children who display SNAs also show a more mature representation of numbers (Opfer et al., 2010). In summary, these studies suggest that SNAs do not originate from symbolic number knowledge and reading habits but rather by early informal cultural practices associated with counting in peripersonal space (see Núñez, 2011).

However, children may not solely exploit the space surrounding their body to count. Rather, they might count on different spaces. Particularly, while peripersonal space defines a spatial region interfacing the body with the environment, the personal space is occupied by the body itself (Cardinali, Brozzoli & Farnè, 2009). Interestingly, direct bodily sensorimotor experience has been suggested to contribute to shaping SNAs. Specifically, finger counting is largely acknowledged to represent an embodied tool on which numbers can be mapped (Andres, Di Luca, & Pesenti, 2008). Notably, during the course of development, it is generally accepted that fingers functionally contribute to support and consolidate a mature counting system (Butterworth, 2005; Di Luca & Pesenti, 2011; Fuson, 1988; but see Crollen, Seron, & Noël, 2011 and Crollen, Mahe, Collignon, & Seron, 2011). Accordingly, some authors proposed that the space within (i.e., fingers) and between (i.e., left versus right) our own hands might affect the origin of SNAs (Fischer & Brugger, 2011). As a matter of fact, number-space compatibility effects can be determined by individual finger counting routines (Di Luca, Granà, Semenza, Seron, & Pesenti, 2006) or at least be modulated by them (Fischer, 2008; Riello & Rusconi, 2011; but see Plaisier & Smeets, 2011). Importantly, whether the direction of finger counting is related to handedness or to cultural factors is still debated (for a discussion, see Previtali, Rinaldi & Girelli, 2011). For instance, most Italian adults (Di Luca et al., 2006) and 4–11-year-old French children (Sato & Lalain, 2008) start to count on their right, dominant hand (but see Fischer, 2008 see also Newman & Soylu, 2013). Therefore, this evidence suggests that distinct space-number mappings, in terms of directionality, might coexist and distinctly emerge in peripersonal and personal space, mainly depending on task demands (Previtali et al., 2011).

The present study addresses the issue of the origin of SNAs by systematically exploring directional routines in pre-reading children. Counting, despite being culturally defined, is a primary and universal activity that preschoolers spontaneously exploit to determine the numerosity of a finite set. Whether using their fingers to keep track of a sequence or pointing to the counted elements in peripersonal space, this process is intrinsically associated with space coding. In the current study, we refer to routines applied to counting external elements as "peripersonal" and to routines applied to counting on fingers as "personal". Accordingly, we address the role of both peripersonal and personal directional strategies to investigate the early presence of SNAs in a large sample of preschoolers. Particularly, we explore the incidence of left-to-right or right-to-left counting preferences before formal schooling, which has been shown to consolidate directional routines associated with written language processing (Chokron & De Agostini, 1995; see also Rinaldi, Di Luca, Henik & Girelli, 2014). Critically, we evaluated the presence of consistent spatial numerical-associations by combining various directional indexes in both peripersonal and personal space. Moreover, following recent evidence (Opfer et al., 2010), we intend to establish the extent to which spatial-numerical consistency, in terms of stable directional mapping between numerical information and space, is related to numerical achievement. Children were presented with various tasks to possibly dissociate the knowledge of numeric symbols and their ability to access numerical representation. We reasoned that a stable association between numbers and space might reflect a more distinct mental representation of numerical information, and this relationship might in turn promote better performance in any task requiring access to this representation. Indeed, representing numerical information in a specific spatial fashion (i.e., linking each number with a precise spatial position) would probably promote the representation of the numerical sequence by increasing numerical discriminability. Accordingly, we expect spatial-numerical consistency to be more strongly associated with children's numerical comprehension (i.e., number line task, give a number