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The spatial representation of numbers and time follow distinct developmental trajectories: A study in 6- and 10-year-old children

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ABSTRACT

Space-number and space-time associations have been a timely topic in the cognitive sciences for years, but evidence from developmental populations is still scarce. In particular, it remains to be established whether space-number and space-time mappings are anchored onto the same spatial frame of reference across development. To explore this issue, we manipulated visual and proprioceptive feedback in a Number Comparison task (Experiment 1) and a Time Comparison task (Expriment 2), in which 6- and 10-year-old children had to classify numerical and temporal words by means of a lateralised response with or without a blindfold (visual manipulation), and with hands uncrossed or crossed over the body midline (proprioceptive manipulation). Results revealed that 10-year-old children were more efficient in associating smaller numbers and past events with the left key, and larger numbers and future events with the right key, irrespective of the visual and proprioceptive manipulations. On the contrary, younger children did so only in the Time Comparison task, but not in the Number Comparison task. In the latter task, 6-year-olds associated small/large numbers with the left/right side of space only in the presence of visual feedback, but not when blindfolded. Taken together, our findings unveil that in school-aged children the spatial representation of number and time develop on different spatial frames of reference: while space-time associations exclusively rely on external coordinates at age 6, space-number associations shift from mixed internal and external coordinates at age 6 to more adult-like external coordinates by age 10.

1. Introduction

Studies conducted in human adults suggest that numbers are represented in a spatial format, typically along a left-to-right continuum, thus suggesting the existence of a *Mental Number Line* (MNL, for a review see de Hevia, Vallar, & Girelli, 2008). This directional bias is testified by the so-called SNARC effect (Spatial Numerical Association of Response Codes, SNARC; Dehaene, Bossini, & Giraux, 1993), which indexes faster response times to smaller numbers with left keys, and to larger numbers with right keys in tasks in which numerial size is task-irrelevant.

This spatial format of numerical information has been recently reported in non-human animals (Rugani, Vallortigara, Priftis, & Regolin, 2015) and preverbal infants (Bulf, Hevia, & Macchi Cassia, 2016; de Hevia, Addabbo, Girelli, & Macchi Cassia, 2014), suggesting that the coding of numbers into a directional spatial code is likely a developmental default and does not rely on symbolic knowledge or formal education. Nevertheless, various studies have shown that the orientation of the MNL varies according to the

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direction of reading and writing habits (Zebian, 2005), as individuals from Western cultures present a left-to-right MNL, while individuals from cultures in which language proceeds from right to left show a reduced or opposite pattern (Shaki, Fischer, & Petrusic, 2009). Therefore, a potential initial orientation bias for number-space mapping can still be modulated by experience later in life (de Hevia, Girelli & Macchi Cassia, 2012; McCrink & Opfer, 2014; Nuerk et al., 2015).

Interestingly, and similarly to number, temporal information appears to be represented along a spatial continuum, with time typically flowing in a left-to-right direction (i.e., with past/earlier events associated with the left space and future/later events with the right space), thus suggesting the existence of an analogus *Mental Time Line* (MTL, see Bonato, Zorzi, & Umiltà, 2012). Indeed, also time-space mapping is susceptible to the influence of cultural routines, as the MTL has been found to be reversed (i.e., oriented from right-to-left) in cultures adopting right-to-left reading and writing habits (Ouellet, Santiago, Israeli, & Gabay, 2010).

The fact that representation of both number and time appear to possess a spatial organisation is in line with the idea that all magnitude information that can be conceptualized in ordinal (more than/less than) terms would be coded according to a common metric (Feigenson, 2007; Walsh, 2003), and that they are represented through a unitary magnitude system. Indeed, the theory of magnitude (i.e., ATOM model), originally proposed by Walsh (2003; Bueti & Walsh, 2009), claims that there may be one common analog format, in which all quantity information are represented. Numerical magnitude, time, and space would all be represented in a common region of the brain – the parietal lobe –, where the integration of all this information occurs in order to guide action.

However, although a shared spatial format for number and time apparently speaks for a common system operating on these two dimensions, a closer look at studies addressing the spatial frame of rereference of the MNL and the MTL reveals a rather different scenario. Frames of reference refer to coordinate systems that individuals use to code spatial information with respect to the body. Spatial information can be coded as centered on the observer's body (egocentric/body-centered coding) or on external, non-bodily objects (allocentric/object-centered coding). Across development, different sensorimotor experiences contribute to the coding of information on either internal or external frames or reference; for example, tactile perception and localisation are initially mapped on internal/body coordinates, while reading and writing orient attention in the external space (Azañón & Soto-Faraco, 2008).

Studies on blind individuals have recently rekindled the debate on the nature of the spatial frames of reference involved. Indeed, visual experience is known to play a crucial role in shaping the use of internal and external coordinate systems, especially for action control and sensorimotor processing (Crollen, Albouy, Lepore, & Collignon, 2017; Röder, Kusmierek, Spence, & Schicke, 2007). For example, Röder et al. (2007) investigated whether developmental vision induces the default use of external coordinates for action control, by testing congenitally blind, late blind and sighted controls on an auditory-based version of a spatial-compatibility task ('Simon task'), in which participants had to discriminate a low vs. high tone, presented by pressing either a right or left key. When participants performed this task with their arms uncrossed, a compatibility effect, i.e., a response facilitation for stimuli presented on the same side of the hand, even though the stimulus location was task-irrelevant, emerged for all. When participants performed the same task with hands crossed over the body midline, the compatibility effect reversed for the congenitally blind, but not for the late blind and sighted controls. This suggests that late blind and sighted controls used an external frame of reference that made them automatically map their responses to the stimulius position. On the contrary, the congenitally blind used an internal frame of reference that made them automatically map the response to the position of their hands. The authors therefore suggested that (developmental) vision determines whether hand-based/internal or stimulus-based/external frames of reference are automatically used for spatially mapping stimuli/objects.

Accordingly, studies that have investigated whether vision is necessary for the development of a MNL have questioned which frame of reference blind individuals use to represent number along a spatial dimension (Castronovo & Seron, 2007; Cattaneo, Fantino, Tinti, Silvanto, & Vecchi, 2010; Rinaldi, Vecchi, Fantino, Merabet, & Cattaneo, 2015). For example, Crollen, Dormal, Seron, Lepore, and Collignon (2013) compared the performance of three groups of sighted, late blind (i.e., blindness onset after 2 years) and early blind (i.e., blindness onset before 2 years of age) individuals, in a numerical comparison task in which participants were required to respond with their hands either uncrossed or crossed (i.e., left hand in the right visual field, right hand in the left visual field) over the body midline. The hypothesis was that, if participants relied upon an external frame of reference, a SNARC effect should be observed irrespective of hand posture. On the contrary, if participants relied upon an internal frame of reference, their performance was expected to vary as a function of the hands' position with respect to the body midline, thus showing a reversed SNARC effect in the crossed hand condition. Results showed that the SNARC effect was independent of hand posture in the late blind and in the sighted; on the contrary, early blind individuals presented an inverted SNARC effect, suggestive of the adoption of an internal frame of reference for representing numbers. These findings suggest that early visual experience drives the development of an external coordinate system onto which numbers are spatially represented.

Interestingly, research with blind participants have also shown that, contrary to the MNL, the frame of reference onto which the MTL is anchored is not modulate by visual experience accumulated throughout development, nor on hands' posture. Bottini, Crepaldi, Casasanto, Crollen, and Collignon (2015) tested for the presence of a MTL in sighted, early and late blind individuals, and found that all groups responded faster with their left/right hand to words referring to the past/future, irrespective of hand posture (uncrossed vs. crossed). Hence, time seemes to be represented entirely along external coordinates, irrespective of visual experience (for complementary evidence see de la Vega, Eikmeier, Ulrich, & Kaup, 2017).

Taken together, the studies conducted in blind individuals (Bottini et al., 2015; Crollen et al., 2013) suggest that the MNL and the MTL rely upon different spatial frames of reference: while the MNL relies on both internal and external frames of reference (see for a discussion Fischer & Hill, 2004; Müller & Schwarz, 2007; Viarouge, Hubbard, & Dehaene, 2014), the MTL would be anchored exclusively on an external frame of reference. Furthermore, there appears to be a different contribution of vision to the development of the two representations: vision would drive the development of the automatic use of an external frame of reference for number, while it would not play any role in driving the reliance on an external frame of reference for time.