Journal of Numerical Cognition
jnc.psychopen.eu | 2363-8761

PsychOpen
publishing psychology

Theoretical Contributions

Visuo-Spatial Processes as a Domain-General Factor Impacting Numerical Development in Atypical Populations

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Abstract

In the past few years, the role of both domain-specific and domain-general factors on numerical development and mathematics achievement has been debated. In this paper, we focus on the role of visuo-spatial processes. We will more particularly review the numerical abilities of populations presenting atypical visuo-spatial processes: individuals with blindness, hemineglect, children presenting low visuo-spatial abilities, non-verbal learning disorder or Williams syndrome. We will show that math abilities of each population are relatively unique and are not necessarily associated with generalized math impairment. We will show that a better understanding of the strengths and weaknesses of each population gives further insights into our conceptual understanding of the development of numerical cognition. We will finally demonstrate how the comparison across disorders can impact on practical rehabilitation and educational strategies.

Keywords: number, space, blindness, hemineglect, NVLD, Williams syndrome

Journal of Numerical Cognition, 2017, Vol. 3(2), 344–364, doi:10.5964/jnc.v3i2.44

Received: 2016-05-10. Accepted: 2017-04-13. Published (VoR): 2017-12-22.

Handling Editors: Silke Goebel, University of York, York, United Kingdom; André Knops, Humboldt-Universität Berlin, Berlin, Germany; Hans-Christoph Nuerk, Universität Tübingen, Tübingen, Germany

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Over the past years, converging lines of evidence suggested that our representation of number is intrinsically linked to the way we represent other, non-numerical magnitude dimensions. Meck and Church (1983) were the first to speculate about a unique functional mechanism (the accumulator model) that supports numerosity and duration processing. This model was later extended by A Theory Of Magnitude (ATOM; Bueti & Walsh, 2009; Walsh, 2003) that conjectures the existence of a central magnitude system for the processing of numerosity, space and time. At the neurofunctional level, brain areas located along the right intraparietal sulcus (IPS) were accordingly shown to be involved in numerosity, length and duration discrimination (e.g., Bueti & Walsh, 2009; Cohen Kadosh et al., 2005; Dormal, Dormal, Joassin, & Pesenti, 2012; Dormal & Pesenti, 2009). At the behavioral level, several studies demonstrated similarities across different magnitude systems. Discriminating numerosities, surface areas and durations for example leads to similar patterns of performance in babies (Brannon, Lutz, & Cordes, 2006; de Hevia, Izard, Coubart, Spelke, & Streri, 2014; Lourenco & Longo, 2010; vanMarle & Wynn, 2006; Xu & Spelke, 2000; for a review, see Feigenson, 2007). And various similarities have been reported between the discrimination of different magnitude dimensions. The most obvious is probably the obedience to the Weber-Fechner's law (Stevens & Greenbaum, 1966; Teghtsoonian & Teghtsoonian, 1978). This law states that the necessary variation in stimulus intensity needed for an organism to detect a change in its status is a constant proportion of the original stimulus intensity rather than a constant amount. As a consequence of this law, the distance (i.e., the ability to discriminate two numbers increases as the numerical distance between them increases) and size (i.e., at equal numerical distance, the discrimination of two numbers decreases as their numerical size increases) effects typically encountered in numerical judgments (Buckley & Gillman, 1974; Moyer & Landauer, 1967; Restle, 1970; van Oeffelen & Vos, 1982), are also present in most judgments of quantifiable dimensions such as line lengths (e.g., Dormal & Pesenti, 2006; Fias, Lammertyn, Reynvoet, Dupont, & Orban, 2003) and duration of sequences (e.g., Dormal, Seron, & Pesenti, 2006; Droit-Volet, Tourret, & Wearden, 2004).

In this paper, we will focus on the interactions that occur between number and space. The SNARC (Spatial Numerical Association of Response Codes) effect is probably the most commonly cited effect supporting strong links between numbers and space (Hubbard, Piazza, Pinel, & Dehaene, 2005). In response-time paradigms, the SNARC effect corresponds to the fact that relatively large numbers are responded to faster with a right-sided response than with a left-sided response. In contrast, relatively small numbers are responded to faster with a left-sided response than with a right-sided response (irrespective of the hand that is used to respond). This effect is usually used as evidence that (Western) people have an internal representation of numbers magnitude (the mental number line) that is oriented from left to right, with small numbers on the left side of space and large numbers on the right side of space (Dehaene, Bossini, & Giraux, 1993; Fias & Fischer, 2005; Hubbard et al., 2005). The metaphor of the mental number line takes place in what Dehaene (1992, 1997; see also Dehaene & Cohen, 1995, 1997) called the triple code model. This model assumes that numbers are represented in three different codes that are related to specific tasks (Dehaene, Piazza, Pinel, & Cohen, 2003). First, there is the analogue magnitude code which corresponds to the mental number line and which is, according to the model, the only code that includes semantic knowledge about numbers. This code is therefore used in magnitude comparison and approximation tasks. Second, there is a verbal word frame, which is activated whenever sequences of number words are manipulated. It would therefore be used for retrieving well learned arithmetic facts such as multiplication tables. Third, there is the visual Arabic number form which represents numbers as strings of Arabic digits and which is used for multi-digit calculation and parity judgments (Dehaene & Cohen, 1991).

In this paper, we will not review the voluminous evidence of the number-space interaction that have been reported in typical populations. We will rather approach the intrinsic relation between the development of numerical and spatial abilities using an alternative perspective. We will describe several studies examining the numerical abilities of populations presenting atypical visuo-spatial processes. Likewise, some researchers have made important statements about what can be learned about relations between spatial and numerical processing from studying atypical populations (e.g., Turner syndrome, Down syndrome, Neurofibromatosis ADHD, Spina Bifida, the deaf, velocardiofacial syndrome and Fragile X syndrome). Mazzocco, Quintero, Murphy, and McCloskey (2016) for example stated that "Evidence from studies of three genetic disorders [22q11.2 deletion syndrome, fragile X, and Turner syndrome] and of typical development suggests that impairments in visuospatial representations, spatial attention, and processing of number and space can cascade into problems acquiring basic numerical and arithmetical abilities (p. 342)". The 22q11.2 deletion syndrome was indeed shown to lead to early developmental changes in the structure and function of clearly delineated neural circuits for basic spatiotemporal cognition. During childhood, this dysfunction cascades into impairments in basic magnitude and then numerical processes, because of the central role that representations of space and time play in their construction. This has been proposed to be due to "spatiotemporal hypergranularity" (Simon, 2008); that is the increase in grain size and thus a reduced resolution of mental representations of spatial and temporal information.

In this paper, we will focus on five populations: individuals with blindness, hemineglect, children presenting low visuo-spatial abilities, children with non-verbal learning disability and people with Williams syndrome. We chose these populations to avoid redundancy with Mazzocco et al. (2016) and to examine different aspects of what is called "atypical visuo-spatial processes": the absence of purely visuo-spatial processes associated to blindness, the neglect of one hemispace in hemineglect and weak or deficient visuo-spatial processes in people with NVLD and WS. After specifying the atypical spatial processes specific to each population, we will explore whether these atypical spatial processing may alter the cognitive representation of numbers and the foundations of mathematical abilities (subitizing, counting, estimation, and calculation). Spatial-numerical associations, the underlying mental representation of numbers and various numerical skills will therefore be described and reviewed in each of these populations. Given that numbers are potentially represented in three different codes (Dehaene et al., 2003), it is possible that deficits in visuo-spatial processes selectively affect the tasks relying on the spatial mental number line while keeping intact the tasks involving the verbal code (e.g., multiplication, counting). Moreover, the diversity of disorders addressed in this special issue will provide us the opportunity to make comparisons across disorders. These comparisons will address a number of issues including whether specific visuo-spatial deficits (the lack of any visuo-spatial processes in the blind; the neglect of one hemispace in neglect patients and deficient visuo-spatial processes in the NVLD and WS people) are associated with specific or common numerical difficulties. By providing information about how visuo-spatial processes contribute to mathematical learning, the study of atypical populations will finally provide rare insights into education and rehabilitation practices.

Interactions Between Number and Space in Individuals With Blindness

As the visual system provides the most accurate, reliable and dominant spatial information about our surroundings (e.g., Alais & Burr, 2004; Charbonneau, Véronneau, Boudrias-Fournier, Lepore, & Collignon, 2013), it is considered as the primary sense when spatial processing is at play and is thought to instruct the development of spatial maps in other sensory modalities (Knudsen & Brainard, 1991; Knudsen & Knudsen, 1985; Wallace & Stein, 2007). Therefore, it could be suggested that the mapping of numbers onto space depends on visual experience (Cooper, 1984; Simon, 1997).

In this sense, studying numerical development in the blind may increase our understanding of the role vision plays in scaffolding spatial-numerical interactions. Does early blindness[i] prevent the development of these interactions and then the development of numerical abilities?

A first surge of studies suggested that the lack of vision did not preclude the development of a left-to-right oriented mental number line. Blind and sighted adults were for example shown to present a classic SNARC effect in two numerical comparison tasks (to 5 and to 55) and in a parity judgment task (Castronovo & Seron,

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2007a; Szücs & Csépe, 2005). In addition to presenting the same SNARC effect, blind and sighted people were also shown to present the same bisection effects in number bisection tasks (Cattaneo, Fantino, Silvanto, Tinti, & Vecchi, 2011; Rinaldi, Vecchi, Fantino, Merabet, & Cattaneo, 2015). When required to indicate (without calculating) the number midway between two others, healthy and blind responded with numbers smaller than the true midpoint (Cattaneo et al., 2011), an observation reflecting the tendency to over represent the left portion of space (i.e., pseudoneglect effect; see Jewell & McCourt, 2000). In another experiment, blind and sighted people were asked to haptically explore rods of different lengths and indicate their midpoints. All participants behaved similarly (Cattaneo, Fantino, Tinti, Silvanto, & Vecchi, 2010) by bisecting the rods to the left of the actual midpoint. This bias was significantly increased by the simultaneous presentation of an auditory small number and was significantly reduced by the presentation of a large number (see also Blini, Cattaneo, & Vallar, 2013). Finally, executing hand movements in left or right peripersonal space was shown to similarly affect blind and sighted numerical bisection performance (Rinaldi et al., 2015).

While this series of results suggested that the interactions between numbers and space occur regardless of a lack of visual experience, recent studies however moderated this conclusion. Indeed, individuals with early blindness demonstrated a classic SNARC effect in a parity judgment but a reversed SNARC effect with crossed hands in a magnitude comparison task (as if they associated small numbers to their left hand and large numbers to their right hand, irrespective of the hemispace in which the hand was placed) (Crollen, Dormal, Seron, Lepore, & Collignon, 2013). This diverging profile of performance in the blind population suggested that different types of spatial information are engaged in different numerical tasks. Visuo-spatial information would be used in magnitude comparison while verbal-spatial information would be used in parity judgment (Herrera, Macizo, & Semenza, 2008; van Dijck, Gevers, & Fias, 2009). Within this framework, sighted and blind people might differ only in tasks relying on the use of visuo-spatial coordinates (the comparison task), but not in tasks involving a spatial language component (the parity judgment task). Interestingly, it has recently been observed that visual experience does not change the spatial coordinate system that is used to represent the mental time line. When asked to classify temporal words as pertaining to the past or to the future, with the hands uncrossed or crossed over the body midline, blind and sighted behave in a similar way. These data therefore suggested that the mental number line and the mental time line are not necessarily relying on the same mechanisms (Bottini, Crepaldi, Casasanto, Crollen, & Collignon, 2015). These data also highlighted the importance of considering the specific spatial components measured in a particular study.

By adopting an auditory lateralized target detection paradigm, it was finally shown that the attentional shifts generated by the audition of numbers have different electrophysiological correlates in blind and sighted people (Salillas, Granà, El-Yagoubi, & Semenza, 2009). Participants had to detect an auditory lateralized target after the auditory presentation of a large (8 or 9) or a small (1 or 2) number. In the sighted group, the amplitude of the sensory N100 component was modulated by congruency (as previously demonstrated by Salillas, El Yagoubi, & Semenza, 2008): it demonstrated enhanced amplitude when auditory stimuli were presented in a congruent versus incongruent location. The modulation of the N100 component was interpreted as the consequence of a top-down mechanism: the number activated a position on the mental number line which in turn exerted spatial shift of attention over auditory space. The modulation of the N100 has therefore been explained as an amplification of the auditory sensory processes of the sighted. By contrast, in the blind group, congruency only modulated the amplitude of the cognitive P300. The P300 was described as reflecting higher cognitive processes such as retrieval and maintenance of a representation in working memory. The absence of visual input could therefore lead blind people to process numbers in a more cognitive way, relying much more on verbal working memory than on sensory processes (see Castronovo & Delvenne, 2013; Crollen, Mahe, Collignon, & Seron, 2011; Crollen et al., 2014 for similar conclusions).

All these experiments suggest that the interactions between numbers and space occur regardless of a lack of visual experience. However, the qualitative properties of how space is used to represent numerical representations may critically depend on early visual experience. Despite these qualitative differences, it is interesting to note that the lack of vision did not preclude the development of various numerical skills (Castronovo, 2014). Individuals with blindness presented similar accuracy levels in all the tasks described above. They perform even better than sighted in various numerosity estimation tasks (Castronovo & Delvenne, 2013; Castronovo & Seron, 2007b; Ferrand, Riggs, & Castronovo, 2010) and in some calculation experiments involving addition and multiplication operations (Dormal, Crollen, Baumans, Lepore, & Collignon, 2016). Vision is therefore not mandatory for the emergence of numerical-spatial interactions, even though visual experience affects the nature of this relation (Crollen & Collignon, 2012).

Evidence of the Interactions Between Number and Space in Patients Presenting Hemineglect

Insights into the number-space interactions can also be obtained by studying how some specific brain injuries can disturb some specific functions. Patients with unilateral neglect after (mainly right) parietal lesion generally fail to detect targets located in the space contralateral to the lesion or are slow to respond to them (Bisiach & Vallar, 2000, for review). Among the best-known clinical manifestations of neglect is the way patients behave in the line bisection task. When they are asked to mark the midpoint of a line, they misplace it to the right. This misplacement is modulated by line length (Marshall & Halligan, 1989): for very short lines, patients move the midpoint to the left rather than to the right, a paradoxical phenomenon known as the crossover effect. As line length increases, they progressively move the midpoint further to the right (Zorzi, Priftis, Meneghello, Marenzi, & Umiltà, 2006). Interestingly, neglect not only affects perception but has also been shown to affect the contro-lesional side of mental representation (Bisiach & Luzzatti, 1978; Grossi, Modafferi, Pelosi, & Trojano, 1989; Rode, Rossetti, & Boisson, 2001). As numbers are assumed to be mapped onto a left-to right mental representation, the study of hemineglect could permit a test of whether this specific (attentional) spatial deficit also affects numerical processing.

Several neuropsychological studies on hemispatial neglect highlighted how numbers and space are built on shared neural structures. Patients presenting right hemispatial neglect were for example shown to display a similar "rightward" bias in number bisection tasks. Indeed, when asked to give the number midway between two others, they produced numbers larger than the true midpoint (Hoeckner et al., 2008; Zorzi et al., 2006; Zorzi, Priftis, & Umiltà, 2002) as if they were disregarding the left side of the interval on the number line. However, when small numerical intervals are presented, a "cross-over effect" is observed, meaning that, in this case, the bisection performances are deviated towards the left/the smaller numerical values. Interestingly, it has been shown that performance on the number bisection task benefits from prism adaptation (Rossetti et al., 2004) and optokinetic stimulation (Priftis, Pitteri, Meneghello, Umiltà, & Zorzi, 2012), 2 techniques known to exert a positive influence on perceptual neglect. Even if a double dissociation between the line and number bisection tasks has been reported in the literature (Doricchi, Guariglia, Gasparini, & Tomaiuolo, 2005), this dissociation is still consistent with the idea that numbers are spatially organized. It confirms that brain damage can disrupt this organization but they also suggest that the visuospatial operations that are required to manipulate numbers could be different from those that are required by the manipulation of physical lines. While number bisection task taps on a mental representation, line bisection task taps on a perceptual space. Since it has been shown that representational and extrapersonal neglect can doubly dissociate (Guariglia, Padovani, Pantano, & Pizzamiglio, 1993), the above data can be an instantiation of this dissociation.

Numbers were also shown to modulate the representation of visual and haptic space both in healthy individuals and patients presenting right-brain-damaged with and without left unilateral spatial neglect. In this task, participants were asked to estimate the midpoint of visually or haptically explored rods while listening to a small digit ("2"), a large digit ("8"), or a non-numerical auditory stimulus ("blah"). While listening to the small digit shifted the perceived midline leftwards, listening to the large digit shifted the perceived midline rightwards. These shifts were moreover observed independently of the modality of response, both in healthy individuals and in patients presenting hemineglect (Cattaneo, Fantino, Mancini, Mattioli, & Vallar, 2012).

Besides the observations made in bisection tasks, numerical distortions following hemineglect have also been found in symbolic and non-symbolic comparison tasks (Masson, Pesenti, & Dormal, 2013). Indeed, when asked to judge if an Arabic digit or a sequence of flashed dots was smaller or larger than a reference value (i.e., 5), patients with hemineglect presented impaired performances to smaller magnitudes and an enhanced distance effect for stimuli of smaller numerical magnitude than the reference. Interestingly, patients with hemineglect did not present the same bias in a duration comparison task (Masson, Pesenti, & Dormal, 2016). These results therefore question the idea that numbers and durations rely on a common magnitude system (see the ATOM theory proposed by Bueti & Walsh, 2009; Walsh, 2003).

An impact of hemineglect has also been observed in calculation (Dormal, Schuller, Nihoul, Pesenti, & Andres, 2014): patients with left unilateral neglect were selectively impaired in subtraction tasks while being unimpaired in addition operations. They made more errors than controls to subtract large numbers, whereas they were still able to solve large addition problems matched for difficulty and magnitude of the answer (Dormal et al., 2014). A growing body of evidence suggests that arithmetic problem solving involves mechanisms akin to those underlying spatial attention orientation (Andres, Pelgrims, Michaux, Olivier, & Pesenti, 2011; Knops, Thirion, Hubbard, Michel, & Dehaene, 2009a; Knops, Viarouge, & Dehaene, 2009b; Masson & Pesenti, 2014; McCrink, Dehaene, & Dehaene-Lambertz, 2007; Pinhas & Fischer, 2008). Within this framework, arithmetic operations involve shifts of attention along the mental number line in the direction of the operation: a shift of attention toward the right (or toward larger numbers) for addition and toward the left (smaller numbers) for subtraction. Difficulties to attend to the left side of space (as in hemineglect) can therefore specifically hamper the solving of subtraction problems.

In sum, hemineglect seems to induce a general rightward bias observed not only in perceptual tasks but also in experiments examining spatial-numerical associations, the mental representation of numbers and calculation. The overall rightward bias that patients with hemineglect present in numerical tasks at least received 3 different explanations. The first one interpreted the bias as reflecting an inability to attend to the left end of the mental number line (Zorzi et al., 2002). The second one questioned the idea of a functional isomorphism between the representation of number and space in long-term memory. It rather suggested that the difficulties of neglect patients could arise from a defective spatial working memory (Aiello et al., 2012; Aiello, Merola, & Doricchi, 2013; Doricchi et al., 2005; Doricchi et al., 2009; Pia et al., 2012; Rossetti et al., 2011; van Dijck, Gevers, Lafosse, Doricchi, & Fias, 2011). The last hypothesis finally suggests that neglect could arise from a difficulty to shift attention leftward of a reference value (Vuilleumier, Ortigue, & Brugger, 2004).

Interactions Between Number and Space in Children Presenting Low Visuo-Spatial Skills

Studying numerical development of children presenting low visuo-spatial abilities represents another window through which the interactions between numbers and space can be disclosed. Indeed, it has been demonstrated that spatial and mathematical abilities correlate with one another (e.g., Skagerlund & Träff, 2016). However, this correlation could just stem from the fact that many math problems actually require some spatial processing. This is the case for geometry obviously but it is also the case for understanding the positional system of the Arabic code or to correctly position numbers in a complex written calculation algorithm. Only a few research examined whether visuo-spatial weaknesses in children could lead to poor spatial-numerical associations. A study of Crollen and Noël (2015) recently investigated whether visuo-spatial weaknesses in typically developing children of 9-10 years old may affect basic numerical tasks tapping the number magnitude itself (the number bisection, number-to-position and numerical comparison tasks). While children from the low visuo-spatial group presented the classic pseudo-neglect and SNARC effects, they were systematically less accurate as compared to a high visuo-spatial group[ii]. These data therefore suggested that low visuo-spatial abilities did not change the nature of the mental number line but led to a decrease of its accuracy.

Over the past ten years, some sparse studies began to consider populations of children with stronger visuo-spatial deficits, i.e., children suffering from diagnosed non-verbal learning disabilities, and began to examine the impact of this deficit on the development of numerical skills. Beside presenting major difficulties in areas of spatial skills within a context of well-developed psycholinguistic skills (Rourke, 1989), children presenting non-verbal learning disabilities (NVLD) were also shown to present poor visuo-constructive and poor visuo-spatial working memory performances (Mammarella & Cornoldi, 2014). Interestingly, these children are also characterized by academic underachievement in mathematics (Vaivre-Douret et al., 2011), geometry (Mammarella, Giofrè, Ferrara, & Cornoldi, 2013) and written calculation (Mammarella, Lucangeli, & Cornoldi, 2010; Venneri, Cornoldi, & Garuti, 2003). They present lower performance in non-symbolic and symbolic number comparison tasks than typically developing children (Gomez et al., 2015) and failed to demonstrate the classic SNARC effect (Bachot, Gevers, Fias, & Roeyers, 2005). Together, these studies suggested that the link between visuospatial and numerical disabilities may be mediated by a basic abnormality in representing numerical magnitudes on an oriented mental number line. This is the conclusion Crollen and colleagues (Crollen, Vanderclausen, Allaire, Pollaris, & Noël, 2015) reached after having presented number bisection, number-to-position and numerical comparison tasks to children with NVLD. Overall, children with NVLD (mean age: 10 years old) were less accurate than their control peers. They also produced more outlier responses in the number bisection task than control children, that is responses that lie outside the numerical interval (e.g., what's the number midway between 4 and 7? Answer: 9). They were not affected by the presentation order of the numbers constituting the numerical interval to be processed while typical children answered faster for ascending interval than descending interval (e.g, what's the number midway between 4 and 7 versus between

7 and 4?). The NVLD group finally failed to show any SNARC effect in the magnitude comparison task (as in Bachot et al., 2005). These qualitative differences suggest that NVLD might actually lead to a disturbed spatial orientation of the mental number line, the left-to-right orientation being not as salient as in control children.

To conclude, while low visuo-spatial abilities seem to be associated with low accuracy in spatial-numerical association tasks, NVLD seems to be associated with a less accurate and less spatially oriented mental number line. Children with NVLD are therefore able to represent magnitude, but may do so with decreased sensitivity. The studies reported above constituted a first step toward a better characterization of the numerical deficits caused by NVLD. However, the existence of a causal link between impairments of basic numerical processing and mathematic achievement in children with NVLD still has to be explored. Consistently with previous studies showing visuo-spatial working memory and visuo-spatial attentional impairments in children with NVLD (Alloway, 2007; Alloway & Archibald, 2008; Tsai, Chang, Hung, Tseng, & Chen, 2012; Tsai, Pan, Cherng, Hsu, & Chiu, 2009; Wilson, Maruff, & McKenzie, 1997), additional experiments should clearly identify whether there is a direct causal link between specific visuo-spatial functions and the numerical performance of these children.

Interactions Between Number and Space in Children Presenting the Williams Syndrome

The hypothesis that a spatial processing dysfunction could create the foundation of numerical disabilities has finally been tested in some genetic disorders characterized by weaker visuo-spatial abilities than verbal abilities. This is the case for example of Fragile X, Turner and 22q Deletion syndromes (see Mazzocco et al., 2016 for a review). Here, we will focus on Williams syndrome (WS), a rare neurodevelopmental disorder caused by the microdeletion of 20 to 30 contiguous genes on chromosome 7q11.23. This syndrome is marked by severe and global damage of spatial cognition but relatively preserved language and facial processing (Ansari, Donlan, & Karmiloff-Smith, 2007). What makes this population of particular interest to the study of numerical cognition is the opportunity to assess how this particular cognitive profile (poor visuo-spatial ability vs. strong verbal skills) affects the development of math skills.

Within this framework, Ansari and colleagues demonstrated that the (visual) estimation skills (Ansari et al., 2007) and understanding of the cardinality principle (Ansari et al., 2003) were extremely delayed in children with WS. Verbal mental age, but not block construction scores, accounted for the variability in cardinality judgments in children with WS. As the opposite pattern held in typically developing children, this result at least indicates that the understanding of the cardinality principle may emerge from distinct sources. Infants with WS are moreover successful in counting but present a smaller subitizing (i.e., the rapid, effortless and accurate judgment of small sets of entities) range than their control peers (O'Hearn, Hoffman, & Landau, 2011). They are able to judge whether solutions to addition and multiplication problems are correct or incorrect (Krajcsi, Lukács, Igács, Racsmány, & Pléh, 2008). They are successful in reading numbers and in discriminating between small numerosities (Paterson, Girelli, Butterworth, & Karmiloff-Smith, 2006). Infants dishabituate to a novel numerosity (3) after familiarization with arrays of 2 objects. However, they cannot clearly represent the precise nature of numerical changes when number is not confounded with continuous variables such as total area (Van Herwegen, Ansari, Xu, & Karmiloff-Smith, 2008). This specific pattern of assets and deficits nevertheless varies with development such that abstract representations of quantity appear intact during infancy but fail to show the typical developmental trajectory during childhood. Later in development, people with WS indeed fail to exhibit a robust distance effect: they do not take significantly longer to discriminate between arrays that have close numerosities, e.g., 2 vs. 3, than to discriminate those that are far apart, e.g., 2 vs. 6 (Paterson et al., 2006). They also perform more poorly than controls in the symbolic version of the comparison task, when reporting which of two numbers is closest to a target number (O'Hearn & Landau, 2007). Finally, infants with WS exhibit lower acuity than their verbal matched peers in numerosity and length comparison tasks but behave similarly than controls in a duration comparison task (Rousselle, Dembour, & Noël, 2013), again suggesting that the spatial representations of time and number may have different experiential bases (Bottini et al., 2015).

In sum, people with WS show relative strengths on some numerical tasks despite their visuo-spatial impairments. Individuals with WS have particular difficulty on tasks requiring a well oriented mental number line (Paterson et al., 2006). However, they perform quite well in tasks requiring (achievable with) verbal processes (Ansari et al., 2003; O'Hearn et al., 2011). A typically left-to-right oriented mental number line may therefore not be needed for several aspects of mathematical achievement and there are probably other ways to learn some specific math skills. Further studies should therefore examine whether instructional strategies targeting the strengths of people with WS (e.g., verbal skills and memorization) may help them to achieve math skills appropriate to their approximate mental age (O'Hearn & Luna, 2009).

Conclusions

As pointed out by Dennis, Berch, and Mazzocco (2009), "evidence regarding the role and importance of spatial deficits in the mathematical difficulties is highly dependent on the nature and definition of the spatial components at issue, the underlying theoretical perspective and the measures of the spatial constructs employed in a particular study" (p. 83). Co-occurrence does not necessarily indicate causal mechanisms. However, it is interesting to highlight that impairments in visuo-spatial representations, spatial attention and processing of number and space can cascade into atypical basic numerical and arithmetical abilities (Walter, Mazaika, & Reiss, 2009).

In this paper, we reviewed five specific populations, each of them presenting atypical visuo-spatial processes: individuals with blindness, with hemineglect, children presenting low visuo-spatial abilities, NVLD or WS. Until now, it is still difficult to determine which spatial deficits are linked to which numerical difficulties. However, regardless of the precise reasons leading to these group differences, it is interesting to note that, as a group, each population shows atypical numerical abilities. The manifestation of the impairment differs among the groups and among the spatial numerical associations tested. In Table 1, the main findings reported in this review are therefore summarized for each group and organized based on an existing spatial-numerical associations taxonomy (Cipora, Patro, & Nuerk, 2015; Patro, Nuerk, Cress, & Haman, 2014). The central distinction of this taxonomy is based on *non-directional* (extensions) vs. *directional* associations between numerical and physical space. Whereas extension describes certain spatial *qualities* of an object (e.g., its width and height), direction refers to an object's location within certain reference frames (Cipora et al., 2015). In the present paper, examples of non-directional associations include (a) cross-dimensional magnitude processing (e.g., number-related attentional shifts while bisecting rods) and (b) associations of spatial and numerical intervals (e.g., number-to-position task). Directional space representation, on the other hand, specifically includes implicit associations between space and cardinality (e.g., numerical comparison tasks). Other directional associations were reported in the original taxonomy (Cipora et al., 2015) but these associations are not yet studied in the populations examined in this paper.

Individuals with blindness, despite their lack of any visuo-spatial experience, do not manifest any numerical deficits. However, the qualitative properties of the numerical representations critically depend on early visual experience. It was for example shown that blindness could change the nature of the reference frame in which the spatial processing of numbers occurs (Crollen et al., 2013). Indeed, while blindness affects number-space interactions in magnitude comparison, it does not affect the reference frame used in parity judgement (Crollen et al., 2013). In patients with right hemineglect, a general rightward bias was reported in various numerical tasks. Different explanations of this bias were suggested in the literature but all of them pointed space as a possible cornerstone (isomorphism between spatial and numerical space vs. defective spatial working memory vs. difficulty to shift spatial attention toward the left). The patterns of performance presented by children with low visuo-spatial abilities, NVLD or WS are finally very well in line with the idea that spatial dysfunction can cascade into impairments in basic magnitude and then numerical processes. Within this framework, individuals with low-visuo-spatial abilities, NVLD and WS may be able to represent magnitude, but may do so with decreased sensitivity to increments.

The comparison made across disorders suggests that the profile found in each disorder is not necessarily observed in all math-impaired people. Math abilities of each population are relatively unique and are not necessarily associated with generalized math impairment. In addition to highlighting specific pattern of performance in each population, the present review also allows us to draw some "universal" conclusions. First, blindness, hemineglect and WS differentially affect numerosity and duration (time) processing suggesting that these different magnitude systems do not share a common spatial ground. This observation adds to previous transcranial magnetic stimulation (TMS) and neuropsychological evidence that have revealed the presence of a double dissociation between these 2 magnitude systems (Cappelletti, Freeman, & Cipollotti, 2009, 2011; Dormal, Andres, & Pesenti, 2008). It questions the idea that numbers and durations rely on a common magnitude system (see the ATOM theory proposed by Bueti & Walsh, 2009; Walsh, 2003), and suggests that the spatial representations of time and number may have different experiential bases (Bottini et al., 2015). Second, the use of damaged visuo-spatial processes seems to have more negative impact on numerical abilities than the total absence of visuo-spatial processes at birth (when comparing people with low visuo-spatial abilities, NVLD or WS to the individuals with blindness). Indeed, it is interesting to note that people with blindness were shown to present similar (Castronovo & Seron, 2007a; Crollen et al., 2013, 2014) or even better (Castronovo & Delvenne, 2013; Castronovo & Seron, 2007b; Dormal et al., 2016) numerical performances than their sighted peers in a series of numerical tasks. This observation, coupled with the fact that even infants with WS present relative strengths on some numerical tasks (Ansari et al., 2003; O’Hearn et al., 2011), suggest that the numerical system is flexible enough to rely on different kinds of sensory and cognitive strategies to develop. Numerical abilities may therefore emerge from the use of alternative strategies (e.g. verbal skills in WS, enhanced working memory following visual deprivation). There seems to have multiple pathways to math knowledge.

An unexplored question is whether the verbal skills of individuals with WS allow them to learn math information in a different manner than typically developing children. Does this sort of learning provide true insight into basic math concepts? Further studies are needed to better characterize whether magnitude representation in WS is

Table 1

Summary of Group-Based Spatial, Spatial-Numerical and Magnitude Processing.

Groups and their main atypical spatial processes	Spatial-numerical associations				Other magnitude processing
	Extensions		Directions		
	Cross-dimensional magnitude processing	Spatial and numerical intervals	Cardinalities and spatial directions	Quantification and calculation processes	
Blind • Non-visual spatial processes	• Rod bisection influenced by number-related attentional shifts (Cattaneo et al., 2010; Blini et al., 2013) as in sighted • Attentional shifts supported by different electrophysiological correlates (sensory in the sighted vs. cognitive in the blind; Salillas et al., 2009)		• Similar reference frame than the sighted in verbal-spatial tasks (Castronovo & Seron, 2007a) but different frames of reference in viuso-spatial tasks (Crollen et al., 2013) • Pseudo-neglect in number bisection tasks (Cattaneo et al., 2011; Rinaldi et al., 2015)	• ↑ Estimation abilities (Castronovo & Delvenne, 2013; Castronovo & Seron, 2007b; Ferrand et al., 2010) • ↑ Calculation (Dormal et al., 2016)	• Similar reference frame than the sighted to represent the mental time line (Bottini et al., 2015)
Hemineglect • Defective spatial working memory • Difficulty to shift spatial attention toward the left	• Visual and haptic space influenced by number-related attentional shifts (Cattaneo et al., 2012)		• Rightward bias in number bisection tasks (Hoeckner et al., 2008; Zorzi et al., 2002, 2006) corrected by prism adaptation (Rossetti et al., 2004) and optokinetic stimulation (Priftis et al., 2012) • Impaired performance and enhanced distance effect for smaller magnitudes in symbolic and non-symbolic comparison tasks (Masson et al., 2013)	• More errors when subtracting large numbers (Dormal et al., 2014)	• Similar performance than controls in duration comparison tasks (Masson et al., 2016)
Low visuo-spatial abilities		• ↓ Accuracy in number-to position task (Crollen & Noël, 2015)	• ↓ Accuracy in number bisection and numerical comparison tasks (Crollen & Noël, 2015)		
NVLD • Deficient visuo-spatial working memory • Visuo-spatial attentional impairments		• ↓ Accuracy in number-to position task (Crollen et al., 2015)	• ↓ Accuracy in non-symbolic and symbolic comparison task (Gomez et al., 2015) • No SNARC effect (Bachot et al., 2005; Crollen et al., 2015) • More outliers responses and no order effect in number bisection task (Crollen et al., 2015)	• ↓ Mathematics (Vaivre-Douret et al., 2011) • ↓ Geometry (Mammarella et al., 2013) • ↓ Written calculation	
WS • Global spatial deficit			• Good discrimination of small numerosities but no robust distance effect later in development (Paterson et al., 2006) • ↓ Acuity in symbolic comparison task	• Cardinality principle understanding (Ansari et al., 2003) and estimation skills (Ansari et al., 2007) extremely delayed	• ↓ Acuity in length comparison task (Rousselle et al., 2013) • Similar performance than controls in a duration comparison task (Rousselle et al., 2013)

Note. ↓ indicates a decrease of performance relative to controls; ↑ indicates an increase of performance relative to controls

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doi:10.5964/jnc.v3i2.44

qualitatively or quantitatively different than observed in controls (O'Hearn & Luna, 2009). Moreover, while non-visual modalities have been obviously proposed to blind participants, performances of people with NVLD and WS were often examined with visual stimuli. Then, it is difficult to know whether some difficulties (e.g., poor estimation skills in WS) are linked to a poor approximate number system or to poor visual skills. Future research should therefore examine this question.

For now, we could speculate that the very basic difficulty of children presenting visuo-spatial difficulties (NVLD, WS) might not be to process number magnitude per se but might rather be to manipulate numbers in space. However, here again, we still don't know whether this difficulty is restricted to the visual modality or whether it generalizes to other modalities such as touch and audition. Continuing to study this question is particularly important given the good numerical abilities demonstrated by the individuals with blindness. In line with the theories of embodied cognition, some studies already demonstrated that the addition of the visuo-haptic exploration could help healthy adults to learn some abstract concepts more effectively (Bara & Gentaz, 2011; Fredembach, Hillairet de Boisferon, & Gentaz, 2009; Pinet & Gentaz, 2008). In the study of Fredembach and colleagues (2009), adults were asked to learn 15 new arbitrary associations between visual stimuli and their corresponding sounds using two learning methods which differed according to the perceptual modalities involved in the exploration of the visual stimuli. Adults used their visual modality in the ''classic'' learning method and both their visual and haptic modalities in the ''multisensory'' learning one. After both learning methods, participants showed a similar above chance ability to recognize the visual and auditory stimuli and the audio-visual associations. However, the ability to recognize the visual-auditory associations was better after the multisensory method than after the classic one. The advantage of a visuo-haptic training over a visual training was also demonstrated in kindergarten children for letter recognition, handwriting quality (Bara & Gentaz, 2011) and geometry (Pinet & Gentaz, 2008). If children presenting low visuo-spatial abilities were able to acquire a haptic sense of numbers (as observed in individuals with blindness), promoting a (visuo-) haptic teaching of arithmetic could probably boost the development of their numerical competencies.

The study of atypical populations therefore leads to important advances, not only at the conceptual level, but also in practical terms, illuminating educational practices. This is extremely timely and important since methods in mathematics education have received considerable interest in the past few years (Clements & Sarama, 2011; Cohen-Kadosh, Dowker, Heine, Kaufmann, & Kucian, 2013). It is also important because mathematics abilities contribute to many quality of life indicators such as employability, decision making, and participation in work and leisure activities (McCloskey, 2007).

Notes

i) Early blindness is characterized by massive visual disturbances since birth and a complete loss of vision at maximum 5 years of age.

ii) In this study, the mean z-score of three visuo-spatial measures (the NEPSY design copying test, the Rey Complex Figure Test and the Cornoldi Shortened Visuospatial Questionnaire) was used to create the two groups of participants. The high visuospatial group included children who obtained z-scores higher than the 65th percentile. The low visuospatial group included children who obtained z-scores lower than the 35th percentile.

Funding

The authors were supported by the FNRS (MPN, OC), the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 700057 (VC) and the 'MADVIS' European Research Council starting grant (OC; ERC-StG 337573).

Competing Interests

The authors have declared that no competing interests exist.

Acknowledgments

The authors have no support to report.

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