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NUMBER-SPACE ASSOCIATIONS AS INDEXED BY THE SNARC EFFECT

THEIR RELATIONS TO MATHEMATICAL ABILITIES AND ANXIETY
&
THEIR UNDERLYING COGNITIVE MECHANISMS

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&

Their Underlying Cognitive Mechanisms

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Summary

The representation of numerical quantities is intrinsically linked with spatial processes. Behavioural evidence for number-space associations comes from the SNARC effect, reflecting faster left-/right-sided responses for small/large digits respectively in binary classification tasks. A question worth investigating is how these basic spatial-numerical mappings relate to mathematical learning and thinking. Firstly, I will therefore determine whether number-space associations, as indexed by the parity SNARC effect, relate to math competencies in elementary school children as well as math anxiety in adults. We show that stronger parity SNARC effects not only associate with better arithmetical abilities in the relatively younger children, but also relate to greater math anxiety in adults. Secondly, I will focus on the spatial coding mechanisms underlying number-space associations, such as the SNARC effect. Although the mental number line has been the dominant explanation, recent theories suggest that number-space associations might rather arise from either verbal-spatial polarity coding or the activation of numerical magnitudes within a spatial sequence temporarily stored in WM. We show that the spatial nature of the coding processes underlying the SNARC effect varies intra-individually depending on the implicit or explicit nature of the numerical task and on the task instructions. Moreover, the extent of this intra-individual variance is conditional upon inter-individual differences in visualization profile and arithmetic performances. By interpreting the relations between the parity SNARC effect and math abilities as well as anxiety in light of the different spatial coding mechanisms underlying this effect in the different contexts and individuals, this work significantly advances our understanding of the cognitive processes contributing to mathematical development.

Table of Contents

1 General Introduction

I don’t think I need to tell you that mathematics is important in our everyday lives. Girls, imagine you could not keep track of the money you spend during shopping or the calories you consume whilst eating a giant piece of cake (and of course the time you need to run on the treadmill to make up for your feast). Boys, imagine you could not understand the meaning of speeding limits (regardless of ignoring them anyway) or the score whilst watching your favourite football team play? Would life be worth living? Definitely not!

Mathematical competencies are crucial for success in Western societies. In fact, they have a greater impact on earning potentials than literacy or intelligence (Boissiere, Knight, & Sabot, 1985; Dougherty, 2003; Rivera-Batiz, 1992; Rose & Betts, 2001). Nonetheless, an estimated 19% of working age adults across OECD (Organization for Economic Co-operation and Development) countries suffer from below-functional numeracy skills (OECD, 2013). In addition, the prevalence of math anxiety, an affective condition typically associated with poorer math skills, is around 30% in 15-year-old students (OECD, 2013). Moreover, approximately 7% of children suffer from a developmental mathematical learning disorder, termed dyscalculia, preventing them from acquiring adequate math skills (Butterworth, Varma, & Laurillard, 2011).

The negative consequences of poor numeracy are far-reaching and drastically affect life outcomes (Bynner & Parsons, 2006). Weak numeracy skills not only associate with less financial wealth (Banks, O'Dea, & Oldfield, 2011), but also contribute to unemployment and restrict access to job opportunities within the work place (Bynner & Parsons, 2006). They also relate to socio-economic deprivation as well as lower socio-economic status (DfES, 2003). In addition, poor numeracy is linked to greater criminality, with 25% of juveniles in custody displaying numeracy skills below that of an average seven-year-old child (Social Exclusion Unit, 2002).

Considering the negative consequences of poor numeracy skills, it is important to get a better understanding of the cognitive mechanisms underlying the adequate development of mathematical competencies. This will not only help foster mathematical abilities in typically developing individuals, but also enable the design of improved diagnostics and rehabilitation for individuals suffering from poor numeracy.

2 Mathematics

Many factors contribute to the adequate development of mathematical skills, including not only domain-specific core numerical abilities, but also domain-general cognitive factors such as working memory (WM) and spatial skills as well as non-cognitive affective variables like math anxiety. All these different factors and their relations to mathematical abilities will be discussed in the following sections.

2.1 Cognitive Factors

2.1.1 Domain-Specific Cognitive Factors

2.1.1.1 Core Numerical Abilities

Core numerical competencies include the abilities to quickly apprehend, without counting, the quantity of collections of up to four objects, a process referred to as subitizing (Starkey & Cooper, 1980; Wynn, Bloom, & Chiang, 2002), and to discriminate between larger collections of objects via approximation (Halberda & Feigenson, 2008; Libertus & Brannon, 2010; Starr, Libertus, & Brannon, 2013; Xu & Spelke, 2000). These core numerical abilities are expressed spontaneously in human infants, immediately after birth and independently of cultural influences, language, or educational level (Izard, Sann, Spelke, & Streri, 2009). They probably rely on two inherent number and magnitude systems: the object tracking system (OTS) or parallel individuation system, mediating the exact representation of quantities of up to four items (e.g., Piazza, 2010), and the approximate number system (ANS), underlying the approximate representation of larger non-symbolic numerical values (Butterworth, 2005; Dehaene, 2011; Feigenson, Dehaene, & Spelke, 2004; Geary, 2007).

At later developmental stages, numerical symbols then acquire their meanings either by being mapped onto these pre-existing non-symbolic approximate representations (Mundy & Gilmore, 2009) or via the development of a new, more precise representation that is distinct from the non-symbolic one (Sasanguie, De Smedt, & Reynvoet, 2015; see also Noël & Rousselle, 2011; Sasanguie, Defever, Maertens, & Reynvoet, 2014). According to the latter hypothesis, the development of these exact symbolic representations is mediated by the OTS in that small numerical symbols are first mapped onto this system (see also Benoit, Lehalle, & Jouen, 2004; Sarnecka & Lee, 2009; Slusser, Ditta, & Sarnecka, 2013). The combination of these associations together with the increasing knowledge of the counting list are then used to infer critical principles of the numerical system, such as order and the successor function (see developmental model of Carey, 2001, 2004, 2009). These principles are then gradually applied to larger symbolic numbers, resulting in the complete understanding of the symbolic numerical system.

Basic non-symbolic and symbolic numerical representations are most frequently assessed using the magnitude comparison task (Ansari, 2008; Dehaene, Dupoux, & Mehler, 1990; Moyer & Landauer, 1967). In this task, participants compare either two sets of dots, thereby indexing the acuity of their ANS, or two Arabic digits, assessing their symbolic numerical processing skills. Performances on the non-symbolic and symbolic versions of this task are usually characterized by the Weber fraction and the distance effect respectively. According to Weber's law, the accuracy of discriminating between two numerosities depends linearly on their ratio, and the Weber fraction reflects the smallest ratio of two numerosities that can be reliably distinguished (Halberda, Mazzocco, & Feigenson, 2008). The distance effect reflects the amelioration in performances (i.e., a reduction in error rate and reaction time) for increasing numerical distances and is computed either as a standardized difference score for small versus large numerical distances (e.g., Holloway & Ansari, 2009) or as the slope of a regression where numerical distance predicts reaction time (e.g., De Smedt, Verschaffel, & Ghesquiere, 2009; Schneider, Grabner, & Paetsch, 2009).

The potential importance of non-symbolic and symbolic numerical processing skills for mathematical development has been intensely studied over the past years (for recent meta-analyses, see Chen & Li, 2014; Fazio, Bailey, Thompson, & Siegler, 2014; Schneider et al., 2016), but the extent and persistence of their contributions remain slightly unclear. Especially the relative importance of non-symbolic versus symbolic numerical magnitude processing for more advanced mathematical skills is still debated.

With regard to non-symbolic numerical skills, Libertus, Feigenson, and Halberda (2011) reported that preschool ANS acuity correlated with school math ability. Similarly, Inglis, Attridge, Batchelor, and Gilmore (2011) showed that the Weber fraction measured in 7- to 9-year-olds was related to their math performances. In addition, training on a non-symbolic comparison task improved performances on symbolic math tests (Hyde, Khanum, & Spelke, 2014; Park & Brannon, 2013). Halberda, Mazzocco, and Feigenson (2008) also indicated that ANS acuity, as indexed by the Weber fraction, at the age of 14 correlated with retrospective measures of math skills from 5 years onwards. Moreover, poorer ANS acuity has been reported in children with math learning difficulties compared to typically developing peers (Mazzocco, Feigenson, & Halberda, 2011; Piazza et al., 2010).

Nonetheless, several studies with typically developing children (e.g., Holloway & Ansari, 2009; Sasanguie, Göbel, Moll, Smets, & Reynvoet, 2013), adults (e.g., Inglis, Attridge, Batchelor, & Gilmore, 2011), and children with dyscalculia (e.g., De Smedt & Gilmore, 2011; Rousselle & Noël, 2007) failed to find a relation between non-symbolic number comparison performances and math skills (for reviews, see De Smedt, Noël, Gilmore, & Ansari, 2013; Gebuis & Reynvoet, 2015). These findings thus imply that the innate representation of non-symbolic approximate quantities is not predictive of later math achievement. In addition, Gilmore and colleagues (2013) demonstrated that the relation between non-symbolic comparison performances and arithmetical abilities was purely driven by the performances on incongruent trials requiring inhibitory control (Fuhs & McNeil, 2013), thus suggesting that the observed link between ANS acuity and math skills mainly results from more domain-general cognitive abilities. Furthermore, Lyons and Beilock (2011) indicated that the association between ANS acuity and more complex math abilities was completely mediated by symbolic number-ordering ability, thereby highlighting the potentially greater involvement of symbolic numerical processing skills for math competencies.

With respect to symbolic numerical skills, De Smedt, Verschaffel, and Ghesquiere (2009) provided the first longitudinal evidence for a causal relation between the speed of symbolic number comparisons at the start of formal schooling and individual differences in math abilities in second grade. Subsequently, both symbolic number comparison speed (Holloway & Ansari, 2009; Landerl & Kolle, 2009; Mundy & Gilmore, 2009) and accuracy (e.g., Piazza et al., 2010; Soltész, Szucs, & Szucs, 2010) were shown to correlate with math competencies. Sasanguie, Van den Bussche, and Reynvoet (2012) also reported that children performing well at comparing symbolic digits featured higher scores on a curriculum-based math achievement task one year later. In addition, children's symbolic numerical processing skills at primary school entrance were predictively related to their future single-digit arithmetical abilities as well as their reliance on arithmetic fact retrieval from long-term memory (Vanbinst, Ghesquière, & De Smedt, 2015). Importantly, these longitudinal associations were not explained by intellectual ability, WM, processing speed, or the children's general math knowledge. In this line, Goffin and Ansari (2016) also showed that the size of the symbolic numerical distance effect explained unique variance in math competencies even after controlling for inhibition capacities. Most interestingly, however, symbolic numerical processing skills were also the best predictor of math achievement when compared to the predictive effects of non-symbolic numerical performances (Sasanguie et al., 2013). This particular importance of symbolic over non-symbolic number skills for math competencies was also confirmed in the meta-analysis by Schneider et al. (2016). They statistically contrasted the effect sizes of non-symbolic and symbolic numerical processing as predictors of math achievement and found that the average effect size was significantly higher for symbolic than for non-symbolic magnitude comparisons. These findings thus suggest that symbolic numerical meaning rather than the representation of non-symbolic numerical quantities plays a crucial role in the adequate development of mathematical competencies.

Nonetheless, despite the strong relation between symbolic numerical processing skills and math competencies, their association likely depends on age (e.g., Holloway & Ansari, 2009; Sasanguie, De Smedt, Defever, & Reynvoet, 2012; Sasanguie et al., 2013) as well as the measures used to assess math performances (e.g., Holloway & Ansari, 2009; see also meta-analysis by Schneider et al., 2016). Holloway and Ansari (2009) for instance showed that the size of the symbolic distance effect was related to math achievement particularly in 6-year-olds, but that the strength of this relation was already diminished by 8 years of age. In addition, these authors found that performances on the symbolic number comparison task correlated with a timed mathematics fluency subtest, but not with an untimed calculation subtest of the Woodcock–Johnson III Tests of Achievement.

2.1.2 Domain-General Cognitive Factors

Apart from the importance of domain-specific core numerical abilities for mathematical success, domain-general cognitive factors such as WM and spatial skills also play a crucial role in formal mathematical development.

2.1.2.1 Working Memory

A relation between WM and math skills is commonly reported (for reviews, see Bull & Scerif, 2001; DeStefano & LeFevre, 2004; Mazzocco & Kover, 2007; Raghubar, Barnes, & Hecht, 2010; for meta-analyses, see Friso-van den Bos, van der Ven, Kroesbergen, & van Luit, 2013; Peng, Namkung, Barnes, & Sun, 2016; Swanson & Jerman, 2006). Greater WM capacity in children is for instance associated with better counting performances (Kyttälä, Aunio, Lehto, Van Luit, & Hautamäki, 2003), number line estimations (Geary, Hoard, Byrd-Craven, Nugent, & Numtee, 2007), and nonverbal math problem solving skills (LeFevre et al., 2010; Rasmussen & Bisanz, 2005). WM in children also explains unique variance in written and verbal calculations and word problems (Andersson, 2008; Bull & Scerif, 2001; Lee, Ng, Ng, & Lim, 2004; Simmons, Willis, & Adams, 2012; Swanson, 2004; Zheng, Swanson, & Marcoulides, 2011). In addition, it is related to more basic numerical abilities such as symbolic and non-symbolic numerical magnitude comparison performances (Simmons et al., 2012; Xenidou-Dervou, de Smedt, van der Schoot, & van Lieshout, 2013; but see e.g., Andersson & Ostergren, 2012, for the lack of significant association). WM also associates with math competencies including mental arithmetics and word problems in teenagers (Kyttälä & Lehto, 2008) as well as with more complex algebraic and geometric problem solving skills in adults (Reuhkala, 2001).

Nonetheless, there are substantial differences in the amount of variance in math performances that can be explained by WM (e.g., Andersson & Lyxell, 2007; Meyer, Salimpoor, Wu, Geary, & Menon, 2010; Passolunghi & Siegel, 2004). Such variations depend amongst others on the specific math domain under consideration. For instance, the meta-analysis by Peng, Namkung, Barnes, and Sun (2016) revealed that the relation between WM and mathematics was strongest for word problem solving and whole number calculations compared to geometry or algebra. In addition, multi-digit calculations showed a stronger relation to WM than single-digit operations (DeStefano & LeFevre, 2004).

The relation between WM and math performances also varies depending on age, math proficiency level and associated strategy use. Different WM components are for instance involved in arithmetic problem solving at different developmental stages. While visuospatial WM is particularly important in younger children who still heavily rely on finger counting strategies (e.g., McKenzie, Bull, & Gray, 2003; Raghubar et al., 2010; Rasmussen & Bisanz, 2005), verbal WM plays a greater role with increasing age (e.g., Barrouillet & Lépine, 2005; Geary et al., 2007; Noël, Seron, & Trovarelli, 2004; Raghubar et al., 2010). Age also affects the global reliance on WM resources during math problem solving. While WM generally plays an important role during the initial phases of math learning, less WM resources are required at later developmental stages. This might be explained by an age-related shift in math problem solving strategies from WM-based procedural calculations including counting and transformation towards arithmetic fact retrieval from long-term memory (Ackerman & Cianciolo, 2000; Geary, Hoard, Byrd-Craven, & DeSoto, 2004; Siegler, 1998). In addition, the problem solving strategies of children are usually less automatic and/or efficient than those of adults, consequently depending more on WM resources (Imbo & Vandierendonck, 2007). The latter also agrees with studies reporting stronger relations between WM and math performances in individuals with math learning difficulties compared to typically developing individuals, probably because the former lack efficient strategies to accomplish math tasks and therefore rely more on WM (e.g., Geary et al., 2007; Klein & Bisanz, 2000). WM thus seems especially important during the earlier stages of math learning, when strategies are less automatic and/or mostly based on procedural calculations.

2.1.2.2 Spatial Abilities

Children and adults performing better on spatial tasks usually also feature higher performances on tasks assessing math competencies (e.g., Burnett, Lane, & Dratt, 1979; Casey, Nuttall, & Pezaris, 2001; Geary, Saults, Liu, & Hoard, 2000; Lubinski & Benbow, 1992; Robinson, Abbott, Berninger, & Busse, 1996; for a review, see Mix & Cheng, 2012). Spatial ability should, however, not be considered as a unitary construct as it consists of multiple skills and concepts, each likely featuring its own connection to mathematical competencies (see Mix et al., 2016). According to the meta-analysis by Linn and Peterson (1985), spatial abilities can be broadly subdivided into three categories, namely mental rotation, spatial visualization and spatial perception. More recently, Uttal et al. (2013) classified spatial skills along intrinsic-extrinsic and static-dynamic dimensions, thereby generating four different spatial categories (i.e., intrinsic static, extrinsic static, intrinsic dynamic, extrinsic dynamic). While the intrinsic-extrinsic dimension distinguishes between skills relying on either the spatial relations within items or those between items, the static-dynamic dimension differentiates between tasks involving either movement or transformation. Mental rotation and spatial visualization skills thus fall within the intrinsic dynamic and intrinsic static dimension respectively, while spatial perception is rather extrinsic and static in nature. For the remainder, I will focus on intrinsic spatial abilities including mental rotation and spatial visualization, as these skills are most commonly assessed in relation to math performances (Mix & Cheng, 2012).

Mental rotation tasks usually require people to recognize the same object in different orientations, thus involving the transformation of the mental representation of items. A clear connection can be evidenced between mental rotation skills and performances on a variety of math tasks. Mental rotation skills in both adolescents and adults are for instance associated with better performances in geometric tasks (Battista, 1990; Delgado & Prieto, 2004; Kyttälä & Lehto, 2008), word problems (Delgado & Prieto, 2004; Hegarty & Kozhevnikov, 1999; Kyttälä & Lehto, 2008), as well as mental arithmetics (Kyttälä & Lehto, 2008; Reuhkala, 2001). They are also related to higher math skills in kindergarten children (Carr, Alexeev, Horan, Barned, & Wang, 2015; Kyttälä et al., 2003; LeFevre et al., 2013). In addition, mental rotation ability in 5-year-olds predicts approximate calculation skills at the age of 8 years (Gunderson, Ramirez, Beilock, & Levine, 2012).

Spatial visualization represents the ability to mentally manipulate 2- and 3-dimensional objects and is typically assessed using tasks such as paper folding or block design. Similarly to mental rotation, spatial visualization skills strongly relate to math competencies. Performances on the block design subtest on the WISC are for instance correlated with math skills throughout the entire schooling period from kindergarten up to high school (Johnson, 1998; Markey, 2010). Achievements on the positions in space subtest of the DVPT-2 are also associated with TEMA-2 scores in kindergartners and third graders (Lachance & Mazzocco, 2006; Mazzocco & Myers, 2003). In addition, the ability to copy block patterns relates to counting skills in 6-year-old children (Kyttälä et al., 2003) as well as performances on arithmetic word problems in 12-year-olds (Hegarty & Kozhevnikov, 1999). The spatial visualization scores of 9th graders in the differential aptitude test also significantly predict their geometry and math problem solving skills in 10th and 12th grade (Sherman, 1979). Evidence for the connection between spatial visualization and math skills also comes from the training study of Cheng and Mix (2014). These authors reported that a single 40-min training session involving 2-D mental transformations was sufficient to instantly improve performances on missing term arithmetic problems in children. This beneficial effect of spatial training could, however, not be replicated by Xu and LeFevre (2016). Although their training paradigm improved the children's 2-D mental transformation skills, it did not positively affect performances in number ordering or number line tasks.

Despite the relation between spatial skills and math abilities, the cognitive mechanisms accounting for their association are still poorly understood. Spatial imagery might, however, be a potential candidate linking spatial skills to math performances. More specifically, individuals with better spatial skills are thought to preferentially rely on spatial images during math problem solving, which likely beneficially affects their math performances (Hegarty & Kozhevnikov, 1999; Kozhevnikov, Hegarty, & Mayer, 2002; Presmeg, 1992). While the most frequent distinction in an individual's preferred method of perceiving, thinking, and remembering (Hadfield & Maddux, 1988) was the visualizer/verbalizer (Paivio, 1971), more recent research has indicated that visual imagery can be classified along two dimensions. This approach is known as the Object-Spatial Imagery and Verbal (OSIV) framework (Blazhenkova & Kozhevnikov, 2009; Kozhevnikov, Kosslyn, & Shephard, 2005), suggesting two distinct types of visualizers, namely object- and spatial-imagers. Object-visualizers have low spatial visualization ability and use imagery to construct vivid, richly detailed, and pictorial images of individual objects (Kozhevnikov et al., 2005), whereas spatial-visualizers feature higher spatial visualization skills and rely on imagery to represent and transform spatial relations and to construct schematic and sparsely detailed spatial images (Blazhenkova & Kozhevnikov, 2009; Kozhevnikov et al., 2005). Interestingly, this distinction in object and spatial visualization preferences not only associates with differences in spatial visualization skills, but also relates to different math achievements. While spatial-visualizers are more likely to be highly achieving in math, the use of pictorial representations in object-visualizers negatively relates to their success in math problem solving (Anderson et al., 2008; Hegarty & Kozhevnikov, 1999; Kozhevnikov et al., 2002; Kozhevnikov et al., 2005; van Garderen, 2006). Spatial-visualizers also score higher on number sense and algebraic reasoning tasks than object-visualizers (Chrysostomou, Pitta-Pantazi, Tsingi, Cleanthous, & Christou, 2013). In addition to the use of spatial imagery, the relation between spatial skills and math performances might also be explained by the reliance on higher-level mental strategies involving retrieval and/or decomposition. Higher spatial visualization skills (in girls) are for instance associated with the greater use of more sophisticated retrieval and decomposition strategies (as opposed to counting) during arithmetic problem solving (Laski et al., 2013) and the latter strategies are generally positively associated with math performances (e.g., Carr & Alexeev, 2011; Carr, Steiner, Kyser, & Biddlecomb, 2008). Altogether, the aforementioned findings thus suggest that greater reliance on strategies involving spatial imagery and/or retrieval and decomposition in individuals with higher spatial visualization skills could potentially account for their better math performances.

2.2 Non-Cognitive Factors

Mathematics not only relates to the afore-described cognitive factors, but also depends on affective variables such as math anxiety.

2.2.1 Math Anxiety

Math anxiety can be described as an individual’s negative affective reaction to situations involving numbers and mathematical calculations, which likely disrupts their performances on numerical tasks (e.g., Ashcraft & Moore, 2009; Suárez-Pellicioni, Núñez-Peña, & Colomé, 2016). Considering the relatively high prevalence of math anxiety (OECD, 2013) and the associated decline in math performances (Ashcraft & Moore, 2009; Hembree, 1990; Ma, 1999; Ma & Xu, 2004; Wu, Amin, Barth, Malcarne, & Menon, 2012), it is crucial to better understand its underlying causes to facilitate early identification, prevention, or remediation.

Although greater math anxiety is associated with weaker math performances, it is still unclear whether math anxiety is the cause or rather consequence of poor math abilities. Math anxiety might for instance emerge as a result of the awareness of weaker math performances in the past. Evidence in favour of this idea is provided by Ma and Xu (2004), showing that prior low math skills predicted later high math anxiety, but not vice-versa. Conversely, the meta-analysis by Hembree (1990) rather suggests a reverse association in that poorer math abilities result as a consequence of greater math anxiety. A reciprocal relation might thus be assumed, where math anxiety negatively affects math performances, which in turn intensifies the initial feelings of anxiety (Wu et al., 2012).

Several theories have been proposed to account for the relation between math anxiety and math abilities. According to the *global avoidance theory* by Ashcraft and Faust (1994), individuals with high math anxiety avoid math-related situations and consequently have less practice and become low achieving. An alternative explanation is based on the *competition for WM resources theory* by Ashcraft and colleagues (e.g., Ashcraft & Faust, 1994; Ashcraft & Kirk, 2001; Ashcraft & Krause, 2007). Accordingly, the worrying intrusive thoughts associated with math anxiety consume the limited resources of WM during math problem solving, thereby reducing their availability for the actual task demands, in turn leading to weaker math performances. Finally, the *deficient attentional control theory* (Eysenck, Derakshan, Santos, & Calvo, 2007; extension of the processing efficiency theory proposed by Eysenck & Calvo, 1992; see also Hopko, Ashcraft, Gute, Ruggiero, & Lewis, 1998) suggests that math anxiety disrupts the balance between goal-directed top-down and stimulus-driven bottom-up processes by enhancing the influence of the latter over the former. More concretely, individuals with high math anxiety are influenced to a greater extent by bottom-up exogenous attentional processes and thus more vulnerable to the intrusion of the worrying thoughts associated with math anxiety. At the same time, they rely less on the top-down attentional system necessary to concentrate on concurrent task demands, again facilitating the interference of distractors. The greater vulnerability to distraction and the associated depletion of valuable WM resources necessary for successful task completion then negatively affects math problem solving.

Even though weaker math performances might contribute to greater math anxiety (Ma & Xu, 2004), the latter is generally thought to have multiple origins (for a recent review, see e.g., Suárez-Pellicioni et al., 2016). Considering the heterogeneous nature of the antecedents of math anxiety, only some of its risk factors will be subsequently discussed. According to Devine, Fawcett, Szucs, and Dowker (2012), the factors systematically associated with math anxiety can be classified into three groups, namely environmental, personality, and cognitive variables. Moreover, an association between math anxiety and gender is commonly reported in that women usually feature greater math anxiety than men throughout their entire schooling period (Devine et al., 2012; Hembree, 1990).

When considering *environmental variables*, stereotypes as well as the characteristics and attitudes of teachers and parents have all been suggested to play a critical role in the development of math anxiety. Beilock, Gunderson, Ramirez, and Levine (2010) for instance reported that female elementary school teachers, who were anxious about math, passed their negative attitudes down to their students. In addition, the children's math achievement and anxiety could be predicted by their parents' math anxiety at the end of the school year, when the parents provided frequent help with math-related homework (Maloney, Ramirez, Gunderson, Levine, & Beilock, 2015).

With respect to *personality variables*, self-esteem, self-concept, attitude, confidence and learning behavior have all been causally related to the emergence of math anxiety (Devine et al., 2012). Math anxiety in adolescents could for instance be modelled as a function of their self-regulation skills and self-efficacy beliefs with regard to numerical and arithmetical tasks (Jain & Dowson, 2009).

In addition to these non-cognitive variables, recent observations also highlighted the crucial role of *cognitive predispositions* in the emergence of math anxiety. Namely, deficits in both basic numerical and spatial abilities likely contribute to the development of this affective condition. Children with high math anxiety were for instance reported to feature reduced activity in brain regions known to support numerical processing, such as the dorsolateral prefrontal cortex and posterior parietal lobe, during an addition and subtraction verification task (Young, Wu, & Menon, 2012). Moreover, a strong relation was observed between developmental dyscalculia and math anxiety (Rubinsten & Tannock, 2010). In addition, individuals with high math anxiety differed from controls on tasks as simple as enumerating items in the counting range (Maloney, Risko, Ansari, & Fugelsang, 2010). They also displayed stronger numerical distance effects in both behavioural (Dietrich, Huber, Moeller, & Klein, 2015; Maloney, Ansari, & Fugelsang, 2011) and ERP settings (Núñez-Peña & Suárez-Pellicioni, 2014). Maloney and colleagues (2011) considered these findings as evidence for a less precise numerical magnitude representation (i.e., a deficit in the ANS) in individuals with high math anxiety. Since Dietrich et al. (2015) did, however, not find a relation between math anxiety and the distance effect when using a non-symbolic dot comparison task (i.e., the standard task to measure ANS acuity; De Smedt et al., 2013), but only with performances in symbolic number comparisons, they suggested that impairments of the latter comparison processes rather than a less precise ANS might constitute a risk factor for the development of math anxiety. Individuals with high math anxiety were also shown to perform worse on the paper-and-pencil mental rotation test compared to participants with low math anxiety (Ferguson, Maloney, Fugelsang, & Risko, 2015; Maloney, 2011). Moreover, Maloney, Waechter, Risko, and Fugelsang (2012) reported a strong negative correlation between math anxiety and the spatial visualization scale of the Object-Spatial Imagery Questionnaire (OSIQ; Blajenkova, Kozhevnikov, & Motes, 2006), comprising no math-related content. The aforementioned findings thus collectively suggest that not only environmental influences and personality characteristics, but also inadequacies in basic numerical and spatial processing skills likely constitute a risk factor for the development of math anxiety.

3 Number-Space Associations

The field of mathematics is traversed by a strong connection between numerical and spatial concepts. Not only do math competencies relate to spatial skills (for a review, see Mix & Cheng, 2012), but mathematics in itself is spatial in nature. The value of a digit within a multi-digit number for instance depends on its specific spatial position. A digit at one particular place represents 10 times the value that is codes for at the adjacent position to its right. The importance of spatial layout also concerns arithmetics. We usually note down operands and results at specific spatial locations. Moreover, equations are read in a specific order with spatial positions indicating the relation between different terms. Interestingly, people are sensitive to this spatial layout. Adults perform better on algebra problems when displayed in the conventional format compared to when the distances between the terms are manipulated (Landy & Goldstone, 2007). Similarly, children have difficulties to solve equations in the form (4 + 3 + 5 = 4 + __), even though they readily complete standard forms of the same problem (McNeil & Alibali, 2004). Finally, the entire field of geometry is founded on the idea that numbers can be translated into spatial measures of lengths, areas, and volumes.

Additional evidence for the tight connection between numerical and spatial concepts comes from people reporting to explicitely picture numbers at very precise spatial locations. Already in 1880, Galton indicated that about 5% of his participants described concrete spatial representations of numbers that were clearly visible whenever they had to process numerical stimuli (Galton, 1880, 1881). Later on, Seron, Pesenti, Noël, Deloche, and Cornet (1992) showed that the latter findings were more than incidental observations and confirmed that about 14% of adults experienced such explicit spatial number forms, a phenomenon referred to as spatial sequence synaesthesia (Eagleman, 2009).

Number-space associations can, however, also be evidenced in individuals not consciously experiencing numbers at specific spatial positions (for further details, see section termed "evidence for number-space associations"). Even infants and neonates are shown to intuitively and spontaneously associate numbers with space (for reviews, see de Hevia, Girelli, & Macchi-Cassia, 2012; Rugani & de Hevia, 2016). Importantly, these associations are specific for the spatial dimension, since numbers are not spontaneously related to other dimensions such as brightness (de Hevia & Spelke, 2013). Lourenco and Longo (2010) for instance showed that 9-month-olds spontaneously applied a rule that they had learned across either a numerical or a spatial dimension to the other untrained dimension. More specifically, when these infants were presented with larger objects of a certain color and smaller objects of a different color, they expected the same color-pattern mapping to hold for greater and smaller numerosities respectively, and vice-versa. Similarly, de Hevia and Spelke (2010) reported that when 8-month-olds were habituated to an ordered sequence of numbers, the effect of habituation transferred to an ordered sequence of line lengths. These infants were also able to generalize a learned positive (but not negative) relation between numbers and line lengths to new examples and displayed greater interest in stimuli with the same positive relation. In addition, when presented with unfamiliar numbers and line lengths, they showed an intrinsic preference for positive rather than inverse pairings. 8-month-old infants were also shown to orient faster towards left-/right-sided targets after the central display of small/large numerosities respectively, as opposed to the opposite pattern (Bulf, de Hevia, and Macchi-Cassia, 2015). Infants thus seem to associate small/large quantities with specific spatial locations. Moreover, even neonates reacted when spatial extent and numerical quantity varied in the same but not the opposite direction (de Hevia, Izard, Coubart, Spelke, & Streri, 2014). These findings thus collectively suggest a biological predisposition to relate numerical representations to spatial concepts. Spatial-numerical interactions thus probably constitute an innate cognitive trait.

Further evidence for such a biologically pre-determined association between numbers and space comes from animal studies. For instance, Adachi (2014) found that chimpanzees preferentially ordered numbers in a left-to-right manner, thus probably mapping numerical sequences onto space. More concretely, after being trained to touch in ascending order digits (1-9) that were randomly located on a touch screen, they responded faster when “1” and “9” were presented on the left and right side of the screen respectively, as opposed to the inverse, in a condition where only these two numerals were horizontally displayed. Moreover, Rugani, Vallortigara, Priftis, and Regolin (2015) showed that once familiarized with a target digit, 3-day-old chicks spontaneously associated relatively smaller/larger digits with the left/right space respectively. These observations thus confirm the deep evolutionary roots for number-space associations and the tendency to associate small/large numerals with the left/right side of space respectively.

Altogether, the aforementioned findings suggest that numbers are intuitively and fundamentally spatial in nature. Further evidence for number-space associations (especially in adults) and the cognitive mechanisms potentially accounting for them will be discussed in the following sections.

3.1 The Mental Number Line

A widely recognized concept in numerical cognition accounting for these number-space associations is the mental number line (MNL) (for reviews, see Dehaene, 1997; Hubbard, Piazza, Pinel, & Dehaene, 2005). It reflects the idea that numerical quantities are represented spatially along a horizontally oriented mental axis (Dehaene, 1992; Dehaene, 2011; Restle, 1970). The MNL thus assumes a tight correspondence between the coordinates of external space and the internal representation of numerical magnitudes.

The hypothesis of such a linear mental representation of numerical magnitudes was initially proposed following the observation of the *distance effect*, describing slower and less accurate responses for comparisons between numbers separated by smaller numerical distances (Moyer & Landauer, 1967). The assumption that this phenomenon resulted from the representational overlap between numerical magnitudes then led to the idea that numbers are internally represented as a MNL (Restle, 1970). Accordingly, the activation of numerical magnitude representations on the MNL spreads to neighbouring numerosities, thereby increasing discrimination difficulty for number pairs adjacent to each other, manifesting in the distance effect (cf., Nieder, 2005). However, it should be noted that the distance effect was also alternatively suggested to result from response-related comparison processes rather than the representational overlap between numerical magnitudes (Van Opstal, Gevers, De Moor, & Verguts, 2008; see also neural network model of number processing by Verguts, Fias, & Stevens, 2005).

Conceptually, the MNL adds a spatial dimension to the afore-described ANS. Nonetheless, the spatial version of the MNL only appeared following the first documentation of the so called *spatial–numerical association of response codes (SNARC) effect*, describing faster left-/right-sided responses for small/large digits respectively in binary classification tasks (Dehaene, Bossini, & Giraux, 1993; for preliminary observations, see also Dehaene et al., 1990). This effect thus suggests that the MNL is oriented in a left-to-right fashion, with small/large numbers represented on the left/right side of this continuum respectively.

Although the MNL was originally introduced as the sole explanation for number-space associations and still benefits from considerable credibility in the field of numerical cognition, alternative cognitive mechanisms have now been suggested to potentially underlie the strong connection between numerical and spatial concepts. These alternative accounts will, however, only be considered later in the section termed “alternative accounts for number-space associations”.

3.2 Evidence for Number-Space Associations

Evidence for the interaction between numerical and spatial representations comes from a variety of findings not only in healthy individuals but also in neuropsychological patients. For the time being, these observations will be discussed and interpreted only in light of the MNL hypothesis. How the following phenomena might be explained by spatial coding processes other than the MNL will be discussed in the section termed “alternative accounts for number-space associations”.

3.2.1 Behavioural Evidence

3.2.1.1 SNARC Effect

The most extensively studied and replicated behavioural evidence for number-space associations is without a doubt the aforementioned SNARC effect (Dehaene et al., 1993). It describes the finding that individuals are typically faster on their left/right hand-side for relatively small/large numbers respectively, when doing a binary classification judgement on numbers. Importantly, the left-to-right oriented MNL only emerged as an a posteriori description of the SNARC effect and should therefore not be considered as a principled explanation.

The SNARC effect was first observed in an experiment where numerical magnitude information was relevant for successful task resolution in that individuals judged whether a centrally displayed number was smaller or larger than a given standard (Dehaene et al., 1990). Subsequent experiments, however, demonstrated that numerical magnitude does not need to be task-relevant to obtain the SNARC effect, since it was also observed during parity judgments (e.g., Dehaene et al., 1993; Hoffmann, Mussolin, Martin, & Schiltz, 2014). The SNARC effect was even evidenced in binary classification tasks not depending on number semantics, such as when judging the pointing direction of a geometric shape superimposed on digits (Fias, Lauwereyns, & Lammertyn, 2001; Mitchell, Bull, & Cleland, 2012).

The SNARC effect also appears independently of input modality or notation, since it was observed with visual and auditory number words as well as visual dice pattern (Nuerk, Iversen, & Willmes, 2004; Nuerk, Wood, & Willmes, 2005). It is also evidenced regardless of output effector. Namely, it appeared even when responses were made with crossed hands (Dehaene et al., 1993) or the participants’ feet (Schwarz & Müller, 2006). Moreover, the SNARC effect was evidenced with unimanual pointing responses (e.g., Fischer, 2003; Gevers, Lammertyn, Notebaert, Verguts, & Fias, 2006) or saccades (Fischer, Warlop, Hill, & Fias, 2004; Schwarz & Keus, 2004).

Even though the aforementioned studies were all conducted in adults, the SNARC effect can also be observed in children. Berch, Foley, Hill, and Ryan (1999) for instance reported a parity SNARC effect in children as early as third grade, but not prior to this stage (see also Schweiter, Weinhold Zulauf, & von Aster, 2005). Similar results were obtained by van Galen and Reitsma (2008), observing a SNARC effect in the parity judgment task in 9- but not 7-year-old children. The latter younger children, however, already displayed a SNARC effect when numerical magnitude was decision-relevant in the magnitude classification task (see also Gibson & Maurer, 2016). The absence of a parity (but not magnitude) SNARC effect prior to the age of 9 years then led to the conclusion that magnitude information is probably only automatically accessed from 9 years onwards. Nonetheless, Hoffmann, Hornung, Martin, and Schiltz (2013) observed a SNARC effect in a numerical magnitude-irrelevant color judgment task already in preschool children at the age of 5.5 years. This thus suggests that not the inability to automatically extract numerical magnitude information from symbols but rather the lack of understanding of the parity concept might explain the absence of a parity SNARC effect in children younger than 9 years. This agrees with the observation that Chinese children, who usually learn about parity in preschool (Ministry of Education of the People's Republic of China, 2012), already displayed a parity SNARC effect in Kindergarten at the age of 5.8 years (Yang et al., 2014). Conversely, Western children generally only acquire knowledge about parity in grade 2 (Berch et al, 1999).

3.2.1.2 Attentional Bias Effect

Further evidence for number-space associations comes from the observation that digits can act as directional cues, inducing lateralized shifts of visuospatial attention (e.g., Fischer, Castel, Dodd, & Pratt, 2003; Goffaux, Martin, Dormal, Goebel, & Schiltz, 2012; see also Galfano, Rusconi, & Umiltà, 2006; Ristic, Wright, & Kingstone, 2006). More concretely, the central display of a non-informative small/large digit was shown to facilitate responses to stimuli in the left/right hemifield respectively (Fischer et al., 2003). Similar results were also obtained by Hoffmann, Goffaux, Schuller, and Schiltz (2015), reporting the facilitation of left-

/right-sided target detection following the central display of task-irrelevant small/large digital cues respectively. Importantly, these facilitation effects were specific for uninformative digits as opposed to letters, suggesting that especially numbers are intrinsically spatial in nature compared to other ordered sequences. The attentional bias effect nicely conforms to the idea of the MNL, if we assume that the observed bias in external space reflects an internal shift of attention towards the activated numerical magnitude representation in mental space.

3.2.1.3 Line Bisection Effect

Yet another behavioural effect providing evidence for the automatic influence of numerical magnitude on spatial judgment is the line bisection effect. The perceived midpoint of a physical line is shifted left-/rightwards for lines composed of only smaller/larger digits or number words respectively (Calabria & Rossetti, 2005; Fischer, 2001). In addition, consistent deviations towards the larger number can be observed when bisecting straight lines flanked on either side by numerically-differing task-irrelevant digits (Fischer, 2001).

3.2.1.4 Random Number Generation

Another source of evidence for number-space associations comes from tasks assessing random number generation. Loetscher, Schwarz, Schubiger, and Brugger (2008) reported that in blind-folded adults, head-movements in the left/right direction induced the production of a greater amount of smaller/larger numbers respectively. Similar results were obtained with eye-movements in that the generation of smaller/larger numbers was preceded by left-/rightward eye movements respectively (Loetscher, Bockisch, Nicholls, & Brugger, 2010). In addition, Shaki and Fischer (2014) reported that participants produced a greater amount of smaller/larger numbers when preparing to turn towards the left/right respectively. Interestingly, these individuals were also more likely to turn left-/rightwards after the generation of a small/large number respectively. The spatial bias in random number generation can also be reconciled with the MNL hypothesis, if we assume that vestibular information provided by left-/rightward movements directs spatial attention towards the left/right not only externally (Figliozzi, Guariglia, Silvetti, Siegler, & Doricchi, 2005), but also along the internal representation of numerical magnitudes.

3.2.1.5 Operational Momentum Effect

Apart from the aforementioned evidence for number-space associations when processing individual numerical stimuli, spatial biases are also observed during mental arithmetics. A spatial bias of misjudgement, termed the operational momentum effect (OME), is commonly reported when estimating the outcomes of addition and subtraction problems in that the results of the former and latter are usually over- and underestimated respectively. The OME is generally explained by an overshoot of the attentional shift towards the intended numerical magnitude on the MNL (McCrink et al., 2007; but for an alternative explanation, see McCrink & Wynn, 2009). To give a concrete example, when adults viewed videos of arrays of dots being either added or subtracted from another and then needed to judge whether the subsequently presented numerosity was correct or not, they displayed systematic biases towards larger/smaller values for additions/subtractions respectively (McCrink, Dehaene, & Dehaene-Lambertz, 2007). Such spatial biases of misjudgement were also observed for symbolic numbers (Knops, Viarouge, & Dehaene, 2009; see also Knops, Dehaene, Berteletti, & Zorzi, 2014). In addition, they were evidenced in children (although reversed: Knops, Zitzmann, & McCrink, 2013) and even infants (McCrink & Wynn, 2009).

3.2.2 Neuropsychological Evidence

Evidence for number-space associations also comes from neuropsychological studies including patients with parietal lesions, who usually feature joint deficits of number and space. These studies not only provide evidence for the strong functional connection between numerical and spatial representations, but also indicate that the parietal lobe, a long-known basic neural underpinning of spatial processing (Critchley, 1953; Jewesbury, 1969), additionally encodes numerical information (see also next section termed “neuro-anatomical basis of number-space associations”).

Patients diagnosed with Gerstman syndrome following damage to the inferior parietal lobule of the left hemisphere usually not only feature deficits in the mental transformation of visual images, but also suffer from acalculia (Gerstmann, 1940; Mayer et al., 1999). In addition, hemi-neglect patients with a (right) parietal lesion typically fail to orient their attention to the contralesional (left) hemispace (for a review, see Halligan, Fink, Marchall, & Vallar, 2003), which becomes obvious when bisecting physical lines. They commonly shift their subjective midpoint to the ipsilesional, not-neglected hemispace, such that the line is typically bisected towards the right of its actual midpoint. Zorzi, Priftis, and Umiltà (2002) extended this finding of physical neglect to the numerical domain. When hemi-neglect patients with right-sided lesions were asked to state the midpoint of a verbally given number interval (e.g., 1–9), they exhibited a bias towards a relatively larger number (e.g., 7), similarly to their rightward bias in the physical line bisection task (see also Aiello, Merola, & Doricchi, 2013; for a review, see Umiltà, Priftis, & Zorzi, 2009). This latter finding is particularly strong in supporting the spatial nature of numerical representations, since neither the presented stimuli nor the required responses are inherently spatial. Furthermore, the performances of hemi-neglect patients could be improved not only in the line, but also the number interval bisection task, when wearing prism glasses inducing rightward optical shifts (Rossetti et al., 2004).

The hemi-neglect literature provides compelling evidence for the MNL, since the spatial biases observed in the number interval bisection task in these patients can be easily explained by assuming an isomorphism between physical lines and the mental representation of numerical magnitudes. Accordingly, patients with left-sided neglect in extra-personal space also exhibit a bias towards larger numbers in the interval bisection task, because they fail to orientate their attention towards the smaller numerical magnitudes represented on the left side of the MNL. Evidence for a defective access to the left part of the MNL in those patients is also provided by Vuilleumier, Ortigue, and Brugger (2004). Namely, hemi-neglect patients were shown to be selectively slower to judge numbers smaller than the referent in a magnitude classification task.

3.3 Neuro-Anatomical Basis of Number-Space Associations

Both functional imaging studies and studies on brain-lesioned patients have consistently indicated that the posterior parietal cortex and in particular areas in and around the intraparietal sulcus (IPS) mediate the abstract representation of numerical quantities and as such correspond to the afore-described ANS (Dehaene & Cohen, 1995; Dehaene, Piazza, Pinel, & Cohen, 2003). Pesenti, Thioux, Seron, and De Volder (2000) for instance showed that areas involving mainly the IPS produced activation during numerical magnitude comparisons. This region is also sensitive to the numerical distance effect, since stronger activations were reported for magnitude comparisons of closer digits irrespective of input notation (Pinel, Dehaene, Rivière, & LeBihan, 2001). In addition, lesions in this area were associated with deficits in tasks requiring numerical comparisons and numerosity estimations (Dehaene & Cohen, 1997; Delazer & Benke, 1997; Delazer, Benke, Trieb, Schocke, & Ischebeck, 2006; Lemer, Dehaene, Spelke, & Cohen, 2003). Number comparison performances were also disrupted following transcranial magnetic stimulation to the left inferior parietal lobule directly adjacent to the IPS (Sandrini, Rossini, & Miniussi, 2004). Furthermore, stimulation of the right posterior parietal cortex induced rightward shifts of the numerical midpoint in a number bisection task (Göbel, Calabria, Farnè, & Rossetti, 2006; Oliveri et al., 2004) and also reduced the parity SNARC effect (Rusconi, Turatto, & Umiltà, 2007; see also Rusconi, Dervinis, Verbruggen, & Chambers, 2013). A hemodynamic signature of the SNARC effect was also found in the bilateral IPS using functional near-infrared spectroscopy (Cutini, Scarpa, Scatturin, Dell'Acqua, & Zorzi, 2014). These regions thus seem to be critically involved in the spatial representation of numerical magnitudes. Altogether, parietal regions in and around the IPS likely host the afore-described MNL, thereby mediating the strong connection between numerical and spatial concepts.

According to the well-known triple-code model of number processing postulated by Dehaene and colleagues (Dehaene, 1992; Dehaene & Cohen, 1995; Dehaene et al., 2003), these regions in the IPS are supplemented by two additional circuits – a visual system involved in the recognition and manipulation of Arabic symbols and a verbal system required for counting and arithmetic fact retrieval. While the visual system is attributed to the bilateral occipito-temporal junction in the ventral visual pathway (Dehaene & Cohen, 1995), the verbal system likely relies on temporal peri-sylvian language areas in the left hemisphere (Dehaene & Cohen, 1995) as well as the left angular gyrus (Dehaene et al., 2003). Later, the posterior superior parietal lobe was added to the model (Dehaene et al., 2003), which is involved in attentional functions and visuospatial behaviours such as grasping, eye movement, and pointing. According to Dehaene and colleagues, this latter region plays a key role in linking spatial functions to numerical magnitude processing. Further additions to the initial model were made by Arsalidou and Taylor (2011), highlighting the functional involvement of prefrontal areas. While the inferior frontal gyri are recruited during basic numerical tasks, procedural calculations and more complex multi-step problems involving computations rather depend on the middle and superior frontal gyri respectively (see also Klein et al., 2016). Finally, the hippocampus was proposed as an additional brain area necessary for arithmetic fact retrieval (Klein et al., 2016). It should, however, be noted that the triple-code model together with its extensions describes numerical representations in adulthood and might therefore not be applied to developmental studies.

3.4 Inter-Individual Differences and Development of Number-Space Associations

Despite the well-documented relation between numerical and spatial representations, the directionality and strength of these number-space associations considerably vary between individuals depending on cultural factors and cognitive skills. The size of the parity SNARC effect for instance depends on mathematical proficiency (see also next section termed “the relation between number-space associations and mathematics”). Individuals scoring lower on arithmetic measures usually display more pronounced number-space associations in the parity judgment task (Hoffmann, Mussolin, Martin, & Schiltz, 2014; but see Cipora & Nuerk, 2013). Similarly, participants with math difficulties feature stronger parity SNARC effects than math controls (i.e., people not studying math-related topics), while the weakest parity SNARC effect is evidenced in professional mathematicians (Hoffmann, Mussolin et al., 2014; see also Cipora et al., 2016). The SNARC effect in the parity judgment task also relates to spatial abilities in that individuals with weaker mental rotation skills display stronger parity SNARC effects (Viarouge, Hubbard, & McCandliss, 2014). The latter effect is also shown to be stronger in individuals with weaker inhibition capacities and that are relatively older (Hoffmann, Pigat, & Schiltz, 2014).

In addition to these inter-individual differences in the strength of number-space associations, Shaki, Fischer, and Petrusic (2009) showed that Canadians, reading from left-to-right, associated small/large numbers with the left/right side of space respectively, while the number-space associations of Palestinians, reading from right-to-left, were reversed (see also Zebian, 2005). The orientation of the MNL thus seems to depend on culturally mediated reading habits. This initially led to the assumption that number-space mappings on the MNL only develop after formal schooling through reading acquisition. Support for this idea was provided by studies observing a parity SNARC effect only in 9-year-old children, but not prior to this age (Berch et al., 1999; van Galen & Reitsma, 2008).

The assumption of such a reading account for number-space associations was, however, refuted by studies evidencing spatial-numerical interactions also prior to reading acquisition. Namely, Hoffmann et al. (2013) reported a SNARC effect in 5.5-year-old preschool children, while performing binary color judgments on single Arabic digits. A SNARC effect was also observed in the classical parity judgment task in Chinese kindergarteners at the age of 5.8 years (Yang et al., 2014). Patro and Haman (2012) even observed a SNARC-like effect in 4-year-olds in that they preferentially associated small/large non-symbolic numerosities with the left/right side of space respectively. These findings thus provide evidence against the idea that the association between numerical and spatial concepts is entirely built on the acquisition of reading skills.

However, such evidence for number-space associations prior to formal schooling is not sufficient to claim their innateness. Since the directionality of spatial-numerical interactions was also shown to depend on directionally-relevant cultural experiences other than reading direction, those factors could give rise to the MNL prior to reading acquisition but postnatally. Shaki, Fischer, and Göbel (2012) for instance showed that 3- to 6-year-old preschoolers growing up in England counted from left-to-right, while Palestinian children counted from right-to-left. Individuals whose finger-counting routines started with the right hand were then also less likely to show a regular SNARC effect (Fischer, 2008). In addition, the orientation of number-space associations in preliterates was modulated by spatial-directional training in that left-to-right attentional non-numerical training led to a subsequent left-to-right SNARC-like effect, while right-to-left training reversed it (Patro, Fischer, Nuerk, & Cress, 2016).

The importance of such directionally-relevant cultural experiences for the development of the MNL is, however, more difficult to reconcile with studies reporting number-space associations already in infants and even neonates (de Hevia, Girelli, Addabbo, & Macchi Cassia, 2014; de Hevia, Girelli, & Vallar, 2006; de Hevia, Izard et al., 2014; de Hevia & Spelke, 2009, 2010; Lourenco & Longo, 2010). Nonetheless, these preverbal populations mostly associate numbers and space in an undifferentiated manner without any directional bias or specific linear relation. Namely, infants and neonates merely mapped numerical quantities onto length or size (de Hevia, Izard et al., 2014; de Hevia & Spelke, 2010; Lourenco & Longo, 2010). Moreover, while 7-month-olds preferred increasing magnitudes presented in a left-to-right orientation, no preference was observed for decreasing magnitudes depicted from right-to-left (de Hevia, Girelli et al., 2014). At these earlier developmental stages, numerical magnitudes might thus not yet relate to lateralized spatial codes (i.e., small/left versus large/right), as it is the case in adults. Consequently, number-space associations in infants and neonates might not arise from a left-to-right oriented MNL, which only gradually develops through cultural experiences. This gradual emergence of the MNL agrees with the four-step developmental model by von Aster and Shalev (2007).

Accordingly, the numerical quantity system in the IPS can be subdivided into an implicit core representation of numerical magnitudes and an explicit MNL. While the former inherited system represents the basic meaning of numbers, the later explicit MNL develops only as a final step following linguistic and Arabic symbolization.

Conversely, although the aforementioned findings suggest that the left-to-right oriented MNL might only develop postnatally, some studies have highlighted its potential innateness. Bulf and colleagues (2015) for instance evidenced directional left-to-right mappings also in 8-month-old infants. Namely, the central display of smaller/larger non-symbolic numerosities facilitated the detection of left-/right-sided targets respectively, indicating that even infants spontaneously associate small/large quantities with the left/right side of space respectively. Further evidence for the innateness of the MNL comes from studies reporting such directional spatial-numerical mappings also in animals. For instance, 3-day-old chicks spontaneously associated relatively smaller/larger digits with the left/right space respectively (Rugani, Vallortigara, Priftis et al., 2015). Some authors, however, suggested that the latter direction-specific number-space associations could be explained by a right hemispheric dominance in visuospatial and/or numerical tasks (Emerson & Cantlon, 2015; Hyde, Boas, Blair, & Carey, 2010; Rugani, Vallortigara, & Regolin, 2016) rather than an innate left-to-right oriented MNL (de Hevia et al., 2012; de Hevia, Girelli et al., 2014; Rugani, Vallortigara, & Regolin, 2015). Accordingly, a leftward attention bias in physical and numerical space would explain the preferential association of small/large numerosities with the left/right side respectively. Nonetheless, functional neuroimaging studies have reported a topographical arrangement of numerical magnitudes in the human parietal cortex (Harvey, Klein, Petridou, & Dumoulin, 2013), thereby probably indicating a biological predisposition to organize numerical representations spatially in the brain. This neural map might then determine the organization of numerical quantities on the MNL (see Drucker & Brannon, 2015), thus emphasizing its innateness. As such, cultural experiences might merely calibrate the directionality of an innate MNL, eventually strengthening or counteracting a biological bias.

3.5 The Relation between Number-Space Associations and Mathematics

Considering the strong and potentially innate association between numerical and spatial concepts, one might wonder how the spatial representation of numerical magnitudes on the MNL relates to mathematical development (for a review, see Cipora, Patro, & Nuerk, 2015).

Inferences about the spatial mapping of numerical quantities and as such the disposition of the MNL are usually derived from the number line estimation task (e.g., Berteletti, Lucangeli, Piazza, Dehaene, & Zorzi, 2010; Booth & Siegler, 2006, 2008; Friso-van den Bos, Kolkman, Kroesbergen, & Leseman, 2014; Geary, Hoard, Nugent, & Byrd-Craven, 2008; Siegler & Opfer, 2003; for the original task, see Petitto, 1990). In this task, participants need to estimate the position of a given number on an empty number line labelled only with the start- and end-points (e.g., 0 and 100). Estimation performances (indicated by the mean difference between estimated and actual target position) are then considered as a direct and isomorphic measure of the underlying MNL (e.g., Laski & Siegler, 2007; Opfer & Siegler, 2007; Siegler & Opfer, 2003). Performances on this task are therefore commonly studied in relation to math abilities to determine the importance of spatial-numerical mappings on the MNL for math achievement.

Interestingly, the accuracy of number line estimations strongly relates to math achievement test scores across different age groups (e.g., Booth & Siegler, 2006, 2008), highlighting the potential importance of number-space mappings for math competencies. Sasanguie and colleagues (2013) for instance reported that children who were more accurate at placing Arabic symbols on such an external number line featured higher scores on a curriculum-based math task one year later. This was also confirmed by Schneider, Grabner, and Paetsch (2009), reporting that children's number line estimation performances were a reliable predictor of math achievement. In addition, children with math learning difficulties featured impaired performances on the number line estimation task (e.g., Geary et al., 2008;

Geary, Hoard, Nugent, & Bailey, 2012; Landerl, 2013; von Aster & Shalev, 2007), yet again highlighting the crucial role of the MNL for adequate math development.

Additional evidence for the importance of number-space associations for math skills comes from training studies. Training preschoolers' spatial-numerical interactions in the number line estimation task using whole body movements not only significantly improved their number-space mappings, but also led to better performances in transfer tasks such as additions (Link, Moeller, Huber, Fischer, & Nuerk, 2013; see also Fischer, Moeller, Huber, Cress, & Nuerk, 2015). Similarly, Kucian et al. (2011) reported that arithmetic problem solving skills were improved in both control and dyscalculic children when these children practiced their spatial abilities of positioning a digit on a number line with the game ''Rescue Calcularis''.

Nonetheless, the appropriateness of the number line estimation task for studying the disposition of the MNL and as such its relation to later math skills has been recently criticised. Estimation performances on this task might not directly reflect scaling of an internal number line representation in an isomorphic way and should thus not be used to study the importance of the MNL for mathematics (Link, Nuerk, & Moeller, 2014; Schneider et al., 2009). Number line estimation performances might rather depend on number knowledge (Ebersbach, Luwel, Frick, Onghena, & Verschaffel, 2008), understanding of the place-value structure (e.g., Moeller, Pixner, Kaufmann, & Nuerk, 2009), the adoption of specific solution strategies such as proportion-judgment (Barth & Paladino, 2011; Cohen & Blanc-Goldhammer, 2011; Slusser, Santiago, & Barth, 2013) or even attentional processes (Anobile, Cicchini, & Burr, 2012).

Some alternative measures were suggested to more directly assess the disposition of the spatial representation of numerical magnitudes on the MNL. Link et al. (2014) for instance indicated that performances on an unbounded version of the number line estimation task (with only a start-point and a unit given; Cohen & Blanc-Goldhammer, 2011) might more directly reflect the quality of number-space mappings on the MNL. Performances on this task did, however, not correlate with addition, subtraction or number comparison abilities in fourth graders, even though a significant association was observed for the bounded number line estimation task in the same population. This thus confirms that strategies other than the MNL accounted for any previously reported relations between bounded number line estimation performances and math skills, and generally questions the importance of number-space mappings for math competencies.

Further evidence against the idea that spatial-numerical representations on the MNL might be crucial for mathematical development comes from studies using the SNARC effect to assess the quality of number-space mappings. It should, however, be noted that spatial coding mechanisms other than the MNL were suggested to account for the SNARC effect (see next section). Interestingly, Schneider et al. (2009) reported that the parity SNARC effect was not a reliable predictor of math test scores in fifth and sixth graders. Similarly, Gibson and Maurer (2016) did not observe a relation between the magnitude SNARC effect and math abilities in 7- and 8-year-olds. Conversely, Hoffmann et al. (2013) showed that stronger magnitude SNARC effects related to better number knowledge in Kindergarteners. Relations between the SNARC effect and math skills were also observed in adults, yet in the opposite direction. Namely, Hoffmann, Mussolin et al. (2014) evidenced weaker number-space associations in students of mathematics, physics and engineering than in students of humanities (see also Dehaene et al., 1993). Similar results were obtained by Cipora and colleagues (2016), reporting stronger parity SNARC effects in less proficient individuals compared to professional mathematicians. Conversely, Cipora and Nuerk (2013) failed to find a reliable relation between the parity SNARC effect and math skills, even though they accounted for some of the methodological weaknesses generally preventing significant outcomes (e.g., small sample size, small test scale lengths, etc.). Similar null effects were also observed by Fischer and Rottmann (2005). Findings with the SNARC effect are thus fairly inconsistent, such that it remains unclear whether and under which circumstances number-space associations actually play a role in the acquisition of math skills.

3.6 Alternative Accounts for Number-Space Associations

For decades, the MNL has been the dominant explanation for number-space associations, such as the SNARC effect, and has always benefited from considerable credibility in the field of numerical cognition (for reviews, see Dehaene, 1997; Hubbard et al., 2005). Nonetheless, recent observations have questioned the idea that spatial-numerical interactions might (entirely) result from such long-term visuospatial representations of numerical magnitudes on a potentially innate MNL.

Number-space associations are highly flexible and since the MNL implies a systematic long-term mapping between numbers and space, it cannot provide an explanation for this kind of flexibility. For instance, the digits 4 and 5 induced faster left-sided responses when the numerical interval ranged from 4 to 9, but facilitated right-sided responses for intervals ranging from 0 to 5 (Dehaene et al., 1993; Fias, Brysbaert, Geypens, & d'Ydewalle, 1996), suggesting that the SNARC effect is driven by relative rather than absolute numerical magnitude. Similar results were obtained in a magnitude classification task where the standard reference dynamically changed from trial to trial. Faster left- and right-sided responses were observed for the digit 7 when it was compared to 8 and 6 respectively (Nathan, Shaki, Salti, & Algom, 2009). Moreover, Bächtold, Baumüller, and Brugger (1998; see also Vuilleumier et al., 2004) reported that individuals featured a regular SNARC effect when instructed to imagine numbers on a ruler, while a reversed SNARC effect was observed when digits had to be imagined on a clock face. Shaki and Fischer (2008) also indicated that Russian-Hebrew bilinguals displayed a typical SNARC effect after reading a text in Russian from left-to-right, while reading a text in Hebrew from right-to-left was sufficient to instantly reverse their SNARC effect.

Further evidence against the MNL hypothesis comes from a modified magnitude classification task where participants were required to give close/far instead of left/right responses depending on numerical magnitude. Interestingly, the smaller digits "1" and "4" were associated with “close” responses, while the larger digits “6” and “9” induced faster “far” responses (Santens & Gevers, 2008; see also Antoine & Gevers, 2016). However, from a direct isomorphism between the MNL and the response location, one would have assumed that the digits “4” and “6”, closer to the referent on the MNL, entailed faster “close” responses, while faster “far” responses should have been observed for the digits “1” and “9”, further away from the referent. In addition, the MNL can hardly explain the odd/left and even/right stimulus-response advantage, known as the linguistic markedness of response codes effect (MARC effect; Nuerk et al., 2004), since the spatial associations alternate for adjacent numerical magnitudes.

Findings from the hemi-neglect literature have also questioned the idea of the MNL. No consistent correlation was for instance observed between the severity of hemi-spatial neglect and the extent of the number interval bisection bias (e.g., Doricchi et al., 2009; Rossetti et al., 2011; van Dijck, Gevers, Lafosse, & Fias, 2012). Moreover, a double dissociation was reported between physical line and number interval bisection tasks in that defective attentional orienting towards the left side of physical space was not always associated with a bias towards larger numbers, and vice versa (Doricchi, Guariglia, Gasparini, & Tomaiuolo, 2005). Similarly, van Dijck, Gevers, Lafosse, Doricchi, and Fias (2011) described a patient featuring right-sided extra-personal and representational neglect (as evidenced by a leftward bias in the line bisection task), but a bias towards larger numbers in the number interval bisection task. These findings thus question the idea that numerical magnitudes are internally represented on a horizontally oriented MNL that is isomorphic to the representation of physical lines or at least doubt the assumption that the number interval bisection bias results from a defective access to numerical quantity representations on the MNL.

3.6.1 Verbal-Spatial Account

An alternative explanation for the SNARC effect and other spatial biases in the processing of numerical magnitudes is the verbal-spatial account, which is based on the polarity correspondence principle by Proctor and Cho (2006). According to this principle, the stimulus and response alternatives in binary classification tasks are coded as negative and positive polarities, with response selection being faster in case of a congruency between the polar codes on the stimulus and response dimensions. In this view, the SNARC effect is explained by the polar correspondence between the verbal categorical concepts “small” and “left” (both assigned to e.g., the negative polarity) as well as “large” and “right” (both assigned to the remaining e.g., positive polarity). This spatial stimulus-response congruency is also depicted in the neural network model by Gevers, Verguts, Reynvoet, Caessens, and Fias (2006). Accordingly, small/large digits automatically activate the small/large label respectively and these magnitude labels then activate the spatial left and right labels. As such, if the task requires a left/right response for a small/large digit respectively, responses will be facilitated. Considering that associations between numbers and space result from structural similarities established through polarity coding, the different numerical and spatial representations do not need to be perceptually or conceptually linked. This account thus assumes that the SNARC effect does not arise from a spatially left-to-right oriented MNL, but rather depends on the “verbal coding of space” (Gevers et al., 2010).

Contrary to the MNL hypothesis, the verbal-spatial account can provide an explanation for the flexible nature of the SNARC effect (e.g., Bächtold et al., 1998), since the verbal categorical concepts and/or polarity codes associated with the different numerical magnitudes are determined spontaneously depending on context. This could then also explain the findings from Santens and Gevers (2008) in that the congruency effect observed in their study resulted from an association between the verbal concepts “small” and “close” as well as “large” and “far”. Verbal-spatial polarity coding can also nicely account for the afore-described MARC effect (Nuerk et al., 2004), assuming that the verbal categorical labels odd/even are associated with the verbal-spatial concepts left/right respectively.

Nonetheless, the verbal-spatial account has still no valid explanation for the differential effect of reading direction on number-space associations (Shaki et al., 2009), if we assume that different cultures show similar associations between valence and space (i.e., good/bad are always associated with right/left respectively, Casasanto, 2009). Moreover, it remains unclear how this account might explain number-space associations in tasks without lateralized responses such as in random number generation (Loetscher et al., 2008) or digit string bisection (Fischer, 2001) tasks. Fischer and Shaki (2014), however, argued that the latter spatial biases could still reflect the creation of bipolar continua for both stimulus and response dimensions and the resulting congruency effects.

The verbal-spatial account is also more difficult to reconcile with number-space associations observed in preverbal infants, let alone non-verbal animals (for a review, see Rugani & de Hevia, 2016). Although English-speaking children already start to develop spatial language at the age of 2, mastery takes a couple of years (Kuczaj & Maratsos, 1975; Johnston, 1984; Sowden & Blades, 1996). Moreover, while 5-year-old children already have adult-like mastery of the verbal concepts “front” and “back”, they still struggle with the concepts “left” and “right” (Kuczaj & Maratsos, 1975). Children usually only acquire egocentric left and right between the ages of 5 and 7 (Hermer-Vazquez, Moffet, & Munkholm, 2001). In addition, the ability to rely on the phonological system to verbally recode visually presented information only arises at the age of 8 years (Pickering, 2001). Children younger than this age are usually not able to generate verbal codes for visual stimuli and therefore solely rely on their visual storage processes. In this line, 5-year-old children were shown to exclusively rely on visuospatial coding in tasks such as wayfinding and picture recall, while a phonological approach was more commonly used only after 8 years of age (Fenner, Heathcote, & Jerrams-Smith, 2000; Palmer, 2000). The verbal-spatial account might thus merely serve as an additional spatial coding process that modulates number-space associations at later developmental stages, once language with its verbal coding mechanisms have become available (see also Patro, Nuerk, & Cress, 2016).

3.6.2 WM Account

A final alternative explanation for number-space associations was provided by Fias, van Dijck, and Gevers (2011), suggesting the crucial involvement of WM in the emergence of spatial-numerical interactions (see also Abrahamse, van Dijck, & Fias, 2016; Fias & van Dijck, 2016; Ginsburg, van Dijck, Previtali, Fias, & Gevers, 2014; Herrera, Macizo, & Semenza, 2008; van Dijck, Abrahamse, Acar, Ketels, & Fias, 2014; van Dijck & Fias, 2011; van Dijck, Gevers, & Fias, 2009). Accordingly, number-space associations, such as the SNARC effect, result from the temporary association between numbers and space in WM, rather than reflecting a long-term MNL representation. More specifically, task-relevant numerical magnitudes are activated in their canonical order within a horizontally left-to-right oriented spatial sequence temporarily stored in WM. Spatial-numerical interactions then result from internal shifts of spatial attention within this encoded numerical sequence, with positions from the beginning/end of the sequence eliciting faster left-/right-sided responses respectively.

Evidence in favour of the WM account is provided by studies showing that the SNARC effect indeed critically depends on the availability of WM resources. The SNARC effect in the magnitude classification task was for instance abolished when participants needed to hold visuospatial information in WM (Herrerra et al., 2008). Van Dijck, Gevers, and Fias (2009) later reported a double dissociation between the type of number processing task and the type of WM load. More concretely, the parity and magnitude SNARC effects could be selectively abolished by a verbal and visuospatial WM load respectively. Furthermore, when individuals judged the parity status of numbers belonging to a memorized sequence of five randomly chosen digits between 1-10, lateralized responses were not associated with numerical magnitude (i.e., no regular SNARC effect), but with the ordinal position of the digits within the encoded sequence, with faster left-/right-sided responses for digits from the beginning/end of the memorized sequence respectively (van Dijck & Fias, 2011). This phenomenon was then referred to as the ordinal position effect. In addition, van Dijck, Abrahamse, Majerus, and Fias (2013) reported that the ordinal position of a digit within a memorized sequence was a better predictor of the ensuing spatial bias than its magnitude. The WM account also conforms to the observation that a SNARC-like effect appears also with non-numerical stimuli featuring an ordinal structure, such as for instance letters (Gevers, Reynvoet, & Fias, 2003) or overlearned newly acquired sequences (Van Opstal, Fias, Peigneux, & Verguts, 2009; Previtali, de Hevia, & Girelli, 2010).

In general, the WM account nicely explains not only the SNARC effect, but also most of the other behavioural effects described earlier, if we assume that information in WM is always spatially encoded and that numbers are automatically stored in WM in their canonical order when performing numerical tasks. It can also account for the flexible nature of number-space associations (e.g., Bächtold et al., 1998; Nathan et al., 2009; Shaki & Fischer, 2008). In addition, WM was shown to contribute to the bias observed in the number interval bisection task in patients suffering from hemi-spatial neglect. Namely, the number interval bisection bias in hemi-neglect patients was associated with damage to prefrontal regions critically involved in WM (Doricchi et al., 2005). Moreover, the bias towards larger numbers in the number interval bisection task, described in the single case study conducted by van Dijck and colleagues (2011), was related to a reduced WM capacity concerning especially the initial items within verbal sequences, thereby further highlighting the potential contribution of (verbal) WM to spatial-numerical interactions.

Nonetheless, the idea that number-space associations exclusively result from the WM account is more difficult to reconcile with the findings from Lindemann, Abolafia, Pratt, and Bekkering (2008). They asked participants to judge the parity status of digits belonging to an ascending, descending or randomly ordered memorized sequence of 3 numbers. Interestingly, the regular SNARC effect disappeared only in the descending order condition. The authors then concluded that storing digits in descending order in WM likely interfered with the long-term spatial representation of numerical magnitudes on the MNL, thereby abolishing the SNARC effect. In this view, numerical magnitudes are thus represented both on a long-term spatially oriented MNL and within a spatial sequence temporarily stored in WM. Further evidence for the parallel existence of long-term as well as WM accounts for number-space associations was provided by Ginsburg and Gevers (2015). In a condition where individuals judged the parity status only of digits belonging to a memorized sequence, a SNARC effect and an ordinal position effect were simultaneously observed. In addition, Huber, Klein, Moeller, and Willmes (2016) indicated that both the ordinal position of a digit within a memorized sequence and its numerical magnitude affected spatial response selection. This thus further substantiates the co-existence of temporarily established number-space associations in WM and long-term spatial-numerical mappings on the MNL. Altogether, the aforementioned results collectively refute the idea of a pure WM account for number-space associations and suggest that numerical magnitudes are more likely activated both on a long-term spatially oriented MNL as well as within a spatial sequence temporarily stored in WM during task execution (but see Abrahamse et al., 2016).

3.6.3 Multiple Different Accounts

Even though the afore-described visuospatial and verbal-spatial accounts are all strong candidates for explaining number-space associations, each of them bears some weaknesses in its potential to account for the entire range of behavioural phenomena reflecting spatial-numerical interactions. While long-term spatial representations of numerical magnitudes on the MNL cannot explain the flexible nature of the SNARC effect (e.g., Bächtold et al., 1998), verbal-spatial polarity coding can hardly account for number-space associations in tasks without lateralized responses (e.g., Fischer, 2001) or in preverbal infants (e.g., Bulf et al., 2015). In addition, it is unlikely that number-space associations exclusively result from the temporary association of the sequential position of numerical magnitudes with space in WM, since a regular SNARC effect is still observed after loading WM with randomly ordered numerical sequences (Ginsburg & Gevers, 2015; Huber et al., 2016; Lindemann et al., 2008). Consequently, both visuospatial and verbal-spatial long-term representations as well as temporarily established associations between numbers and space in WM likely contribute to the full range of behavioural effects reflecting number-space associations.

The idea that number-space associations cannot be reduced to a single spatial coding mechanism, but result from multiple different spatial coding processes depending on contextual factors, finds support in the literature. Van Dijck and colleagues (2009) for instance reported that the parity and magnitude SNARC effects were selectively abolished by a verbal and visuospatial WM load respectively. In addition, when performing a principle component analysis on some of the behavioural markers of number-space associations, the outcome did not reveal a single factor solution, but the data was best explained by a three-component model (van Dijck et al., 2012). Moreover, Müller and Schwarz (2007) reported that different spatial coding mechanisms accounted for horizontal and vertical SNARC effects. Namely, in a task where instructions emphasized either the hand for responding or the location of the response button, the horizontal SNARC effect was always location-based, while the vertical SNARC effect was congruent with the instruction. Finally, hemi-spatial neglect patients displayed stronger SNARC effects for larger numbers in the explicit magnitude classification task, but featured a regular SNARC effect in the parity judgment task with implicit access to numerical magnitude (Priftis, Zorzi, Meneghello, Marenzi, & Umiltà, 2006; Zorzi et al., 2012). These findings thus collectively highlight the heterogeneous nature of number-space associations, suggesting that the different behavioural signatures of spatial-numerical interactions unlikely arise from a single underlying cognitive process.

Conversely, Gevers and colleagues (2010) reported the predominance of verbal-spatial coding in both the parity judgment and magnitude classification tasks, when pitting both verbal-spatial and visuospatial accounts directly against each other. In addition, Cheung, Ayzenberg, Diamond, Yousif, and Lourenco (2015) observed a significant correlation between performances in several tasks assessing number-space associations (including parity judgments, magnitude classifications, random number generations and number line bisections), even when partialling out the effects of general cognitive abilities or the participants' reaction times. The latter findings thus rather suggest the activation of a single predominant spatial coding mechanism regardless of context.

Considering these contradictory findings with regard to whether a single predominant spatial coding account or multiple different spatial coding mechanisms might underlie number-space associations, such as the SNARC effect, further research is required to determine if the spatial coding processes explaining spatial-numerical interactions actually vary inter- and/or intra-individually and also the specific circumstances under which such variations might occur. Moreover, the exact spatial nature of the coding account(s) in each of these situations needs to be revealed.

4 Research Questions

I will now focus on the two different yet related research goals pursued in this thesis. The first research question concerns the relations between number-space associations and mathematical abilities in elementary school children as well as math anxiety in adults. The second research question focusses on the spatial coding mechanisms underlying number-space associations in different contexts and individuals, thereby addressing the current debate in the literature regarding the predominance as well as the specific spatial nature of the cognitive processes underlying spatial-numerical interactions. Importantly, the studies presented in this thesis used the SNARC effect to index the strength of number-space associations.

4.1 Number-Space Associations and their Relations to Math Abilities and Anxiety

In ***study 1***, we determined whether and how the parity SNARC effect relates to math abilities in third to fourth grade elementary school children. Studies commonly report a relation between better number line estimation performances and greater math skills (e.g., Booth & Siegler, 2006, 2008; Sasanguie et al., 2013; Schneider et al., 2009), thereby hinting at the important role of number-space mappings for the acquisition of math competencies. Nonetheless, number line estimation performances might not directly reflect the scaling of an internal number line representation in an isomorphic way, but rather depend on number knowledge (Ebersbach et al., 2008), the understanding of the place-value structure (e.g., Moeller et al., 2009), the adoption of specific solution strategies such as proportion-judgment (Barth & Paladino, 2011; Cohen & Blanc-Goldhammer, 2011; Slusser et al., 2013) or even attentional processes (Anobile et al., 2012). Consequently, the number line estimation task might not be an appropriate measure for studying the disposition of number-space mappings on the MNL and as such their importance for mathematical development. Unfortunately, studies using alternative measures, such as the SNARC effect, have mostly yielded inconsistent results regarding the relation between spatial-numerical interactions and more complex math skills. While positive associations between stronger SNARC effects and better math abilities were observed in younger children (Hoffmann et al., 2013), negative relations were reported in some adult studies (Cipora et al., 2016; Hoffmann, Mussolin et al., 2014). Yet other studies did not observe an association between the SNARC effect and math skills (Cipora & Nuerk, 2013; Gibson & Maurer, 2016; Schneider et al., 2009). Considering that these inconsistencies could be explained by differences in the age range of the study populations or the specific tasks used to assess math performances (e.g., Holloway & Ansari, 2009; Sasanguie et al., 2013; Schneider et al., 2016), we determined the relations between the parity SNARC effect and both arithmetical as well as visuospatial math abilities using the "Heidelberger Rechentest", a standardized German math test for elementary school children. Moreover, we assessed whether potential relations between the parity SNARC effect and either of these math abilities might be conditional upon the children's ages.

In ***study 2***, we determined whether and how the parity SNARC effect relates to math anxiety in adults. Recent studies have indicated that stronger numerical distance effects (Dietrich et al., 2015; Maloney et al., 2011; Núñez-Peña & Suárez-Pellicioni, 2014), reflecting less precise numerical magnitude representations (but see van Opstal et al., 2008, for an alternative explanation), as well as weaker spatial abilities (Ferguson et al., 2015; Maloney et al., 2012) were associated with greater math anxiety. These observations thus suggest that inadequacies in basic numerical and spatial skills might represent a risk factor for the emergence of math anxiety. To further elaborate on these findings, we focussed on the parity SNARC effect, capturing the interplay between such basic numerical and spatial concepts, and hypothesized that it might also relate to math anxiety. Considering the negative associations between more pronounced parity SNARC effects and weaker math skills in adults (e.g., Cipora et al., 2016; Hoffmann, Mussolin et al., 2014; but see Cipora & Nuerk, 2013) in addition to the well-established link between poorer math performances and greater math anxiety (Ashcraft & Kirk, 2001; Ashcraft & Moore, 2009; Hembree, 1990; Ma, 1999; Ma & Xu, 2004), we anticipated that stronger parity SNARC effects would be associated with greater math anxiety.

Altogether, these studies should advance our understanding of the involvement of number-space associations, such as the parity SNARC effect, in mathematical learning and anxiety. Getting a better idea of the cognitive processes contributing to the development of math skills and anxiety might not only help foster math abilities in typically developing children, but also enable the design of improved diagnostics and rehabilitation for individuals with math learning difficulties and/or anxiety.

4.2 Number-Space Associations and their Underlying Cognitive Mechanisms

Apart from establishing the relations between number-space associations, such as the parity SNARC effect, and math skills as well as anxiety, it is also essential to better understand their underlying spatial coding mechanisms to get a more complete picture of the specific cognitive processes actually contributing to mathematical development.

Despite the converging evidence that number-space associations, such as the SNARC effect, result from the spatial representation of numerical magnitudes on the MNL, the unique contribution of this long-term visuospatial construct has been recently questioned (e.g., Bächtold et al., 1998; Gevers et al., 2010; Fias et al., 2011; Huber et al., 2016). Alternative theories suggest that number-space associations might rather arise from either verbal-spatial polarity coding (Gevers et al., 2010; Proctor & Cho, 2006) or the activation of numerical magnitudes within a spatial sequence temporarily stored in WM (Abrahamse et al., 2016; Fias & van Dijck, 2016; Fias et al., 2011; Ginsburg et al., 2014; Herrera et al., 2008; van Dijck & Fias, 2011; van Dijck et al., 2014). Moreover, some studies have argued that the interaction between numerical and spatial concepts might depend on multiple different spatial coding processes, whose activational extent varies with task characteristics (e.g., Priftis et al., 2006; van Dijck et al., 2009, 2012; Zorzi et al., 2012).

In ***study 3***, we therefore determined whether the spatial nature of the coding mechanisms underlying the SNARC effect depends on contextual factors such as the implicit or explicit nature of the number processing task. We adopted an individual differences approach and studied the correlation between the parity and magnitude SNARC effects as well as the extent of their associations with arithmetic performances, spatial visualization ability and visualization profile. In addition, we assessed whether the relation between the SNARC effects in implicit and explicit tasks could be moderated by inter-individual differences in these cognitive factors. This should not only further advance our understanding of whether the spatial coding processes underlying the SNARC effect actually vary intra-individually with task characteristics, but also inform us about whether this potential context-dependency is conditional upon inter-individual differences in cognitive variables. It should, however, be noted that this study was not designed in a way that it could directly highlight the visuospatial and/or verbal-spatial nature of the coding mechanisms potentially contributing to the SNARC effect in the different conditions and individuals.

In ***study 4***, we therefore specifically determined whether the SNARC effect in the magnitude classification task results from visuospatial and/or verbal-spatial coding mechanisms. To pit these two accounts directly against each other and to measure their relative strengths in explaining the magnitude SNARC effect, we used an innovative task designed by Gevers and colleagues (2010) that allowed us to dissociate the confound of both spatial coding mechanisms typically encountered in the classical SNARC paradigm (e.g., faster left-sided responses for small digits might result from an association either between the verbal concepts “small” and “left” or between small numerical magnitudes and the left side of physical space). More specifically, we randomly varied the positions of the verbal labels “Left” and “Right” to appear on the left or right physical response sides, thereby creating word congruent trials (where the verbal labels “Left”/”Right” appeared at their corresponding physical locations) and word incongruent trials (where the verbal labels "Left"/"Right" appeared on the right/left physical response sides respectively). While the visuospatial account is predicted by an interaction between numerical magnitudes and physical response sides regardless of the associated verbal response labels, the contribution of verbal-spatial coding mechanisms is indicated by an association between numerical magnitudes and the verbal response labels irrespective of their side of appearance. Participants were instructed to base their responses once on the verbal labels and once on the physical response sides. This allowed us not only to reveal the specific spatial nature of the coding mechanisms underlying the SNARC effect in the magnitude classification task, but also to determine whether it depends on task instructions, thereby potentially extending the previously reported context-dependency of the SNARC effect (e.g., van Dijck et al., 2009).

Altogether, these studies should not only further clarify whether number-space associations, such as the SNARC effect, result from a single or multiple different spatial coding accounts depending on contextual factors and/or individual characteristics, but also provide valuable information with regard to the exact spatial nature of these coding mechanisms.

5 Study 1

Mathematical Abilities in Elementary School: Do They Relate to Number-Space Associations?

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5.1 Abstract

Considering the importance of mathematics in Western societies, it is crucial to understand the cognitive processes involved in the acquisition of more complex mathematical skills. The present study therefore investigated how the quality of number-space mappings along the mental number line, as indexed by the parity SNARC effect, relates to mathematical performances in 3rd and 4th grade elementary school children. Mathematical competencies were determined using the *Heidelberger Rechentest*, a standardized German math test assessing both arithmetical and visuospatial math components. Stronger parity SNARC effects significantly related to better arithmetical but not visuospatial math abilities, but only in the relatively younger children. These findings thus highlight the importance of spatio-numerical interactions for arithmetical (as opposed to visuospatial) math skills at the fairly early stages of math development. Differential relations might be explained by the use of problem solving strategies relying on number-space mappings only for arithmetic tasks mainly in younger children.

Keywords: Numerical cognition; number-space associations; SNARC effect; mathematical abilities; individual differences; development.

5.2 Introduction

Considering the importance of mathematics in Western societies, it is crucial to understand its underlying cognitive mechanisms and early precursors. Building a thorough knowledge base of the different components of numerical thinking will not only help us foster mathematical abilities in typically developing children, but also enable us to design appropriate diagnostics and evidence-based interventions for children with mathematical learning difficulties. Basic numerical competencies such as the comprehension and manipulation of quantity concepts and their associated symbols (i.e., number words and Arabic digits) are known to be foundational to more elaborate mathematical skills (Butterworth, 1999; De Smedt, Verschaffel, & Ghesquière, 2009; Dehaene, 1997). Over the past decade much research has been dedicated to understand how exactly these basic numerical skills relate to individual differences in performances on more advanced mathematical concepts and procedures (De Smedt, Noël, Gilmore, & Ansari, 2013; Hyde, Khanum, & Spelke, 2014; Libertus, Feigenson, & Halberda, 2011). Considering the crucial influence of especially symbolic numerical representations for later math achievement (Holloway & Ansari, 2009; Lyons & Beilock, 2011; Sasanguie, De Smedt, Defever, & Reynvoet, 2012; Sasanguie, Göbel, Moll, Smets, & Reynvoet, 2013; see also meta-analysis by Schneider et al., 2016), it seems particularly important to thoroughly understand and characterise the developmental trajectory of the comprehension of number symbols to gain better insights into the processes involved in the acquisition of more complex math skills.

The representation of numerical quantities in general and number symbols in particular is thought to be intrinsically linked with spatial processes in typically developed human adults (Dehaene, Bossini, & Giraux, 1993; Dehaene, Dupoux, & Mehler, 1990; Fias, Lauwereyns, & Lammertyn, 2001; Fischer, 2001; Fischer, Castel, Dodd, & Pratt, 2003; Hoffmann, Mussolin, Martin, & Schiltz, 2014; Lammertyn, Fias, & Lauwereyns, 2002; Wood, Willmes, Nuerk, & Fischer, 2008; for a recent review, see also Fischer & Shaki, 2014). A widely recognized concept for these spatial associations in numerical cognition is the mental number line (MNL, for reviews see Dehaene, 1997; Hubbard, Piazza, Pinel, & Dehaene, 2005; Nieder, 2005), reflecting the idea that numerical quantities are represented along a horizontally oriented mental axis (Dehaene, 1992; Restle, 1970) that is universal across humans despite culturally-mediated differences in its direction (mostly left-to-right orientation in Western cultures). According to the four-step developmental model of numerical cognition by von Aster and Shalev (2007), the process of Arabic symbolization constitutes a precondition for the formation of such a spatially oriented MNL. The fourth stage of numerical development is then assumed to be concluded with the establishment of spatial-numerical representations along the MNL at the beginning of primary school (von Aster & Shalev, 2007).

Interestingly, the quality of number-space associations along the MNL has been shown to relate to school-relevant mathematical skills. For instance, Sasanguie, Göbel, Moll, Smets, and Reynvoet (2013) reported that children who were more accurate at placing symbolic digits on an external number line featured higher scores on a curriculum-based math task one year later. The importance of symbolic number line estimation performances for later mathematical skills was also confirmed by other studies (e.g., Booth & Siegler, 2008; Schneider, Grabner, & Paetsch, 2009; Siegler & Booth, 2004). In addition, using whole body movements to train preschoolers' spatial-numerical associations in the number line estimation task not only significantly improved their spatial-numerical mappings, but also increased their performances in transfer tasks including additions (Link, Moeller, Huber, Fischer, & Nuerk, 2013; see also Fischer, Moeller, Bientzle, Cress, & Nuerk, 2011). In line with these findings, Kucian et al. (2011) showed that performances of dyscalculic and control children during arithmetic problem solving were improved when the children practiced their spatial abilities of positioning a digit on a number line with the game ‘‘Rescue Calcularis’’.

Nonetheless, according to Schneider et al. (2009), estimation patterns on the external number line should not be considered as a direct marker for the use of the internal MNL. They reasoned that the two constructs cannot be equated, since the neural properties of the MNL are in no way visually similar to external number lines (e.g., Feigenson, Dehaene, & Spelke, 2004; Nieder, 2005). As a consequence, number line estimation performances should not be used to draw inferences about the disposition of number-space mappings along the MNL and as such to study the relation between the quality of number-space associations and arithmetical abilities. In line with this view, Link, Nuerk, and Moeller (2014), who recently failed to provide evidence for a significant correlation between estimation performances in an unbounded number line task and arithmetical abilities, suggested that the processes additionally assessed in the more commonly administered bounded version of this task (e.g., proportion judgment rather than number-space mappings per se) accounted for any previously reported associations between estimation performances and arithmetical competencies.

A commonly studied performance pattern in numerical cognition that might be more appropriate for assessing an individual's reliance on the MNL is the spatial-numerical association of response codes (SNARC) effect. This phenomenon, firstly reported by Dehaene and colleagues (1993), describes the finding that individuals usually respond faster to small/large numbers with their left/right hand respectively in binary classification tasks. To determine the genuine importance of the quality of spatial-numerical mappings along the MNL for later math competencies, it might thus be more appropriate to focus on number-space associations as indexed by the SNARC effect. Unfortunately, studies assessing the relation between the SNARC effect and more complex mathematical skills are relatively scarce, especially in children. Moreover, the few existing studies have mostly produced inconsistent results. Positive associations were for instance evidenced by Hoffmann, Hornung, Martin, and Schiltz (2013), reporting stronger SNARC effects during magnitude classification tasks in Kindergarten children with better number knowledge (i.e., who could write more Arabic numerals in a correct sequence). Conversely, Gibson and Maurer (2016) did not find a relationship between the magnitude SNARC effect and the TEMA-3 math scores in slightly older children aged between 6 and 8 years. Similarly, no correlation was observed between the SNARC effect in a parity judgment task and mathematical skills in older children attending 5th or 6th grade (Schneider et al., 2009). Null effects were also reported in adults by Bonato, Fabbri, Umiltà, and Zorzi (2007), Bull, Cleland and Mitchell (2013) as well as Cipora and Nuerk (2013). Yet other studies in adults reported negative relationships between stronger number-space associations and weaker math skills. For instance, Fischer and Rottmann (2005) as well as Dehaene et al. (1993) observed less pronounced number-space associations in students of mathematics, physics, or engineering compared to individuals not studying math-related subjects. Similarly, Hoffmann et al. (2014) indicated weaker SNARC effects in math experts compared to math controls (see also

Cipora et al., 2016), while individuals with math difficulties featured the strongest SNARC effects.

Considering the aforementioned studies, it appears that age needs to be considered when studying how performances in mathematical tasks relate to individual differences in the SNARC effect. While positive associations between stronger spatial-numerical interactions and better math abilities were reported at the very early stages of math development, null or negative relations were observed mainly in adults. Similar developmental changes in the relation between basic numerical skills and math competencies have been reported for other measures of basic number processing (e.g., Fazio, Bailey, Thompson, & Siegler, 2014; Holloway & Ansari, 2009; Sasanguie et al., 2013; Schneider et al., 2016). For instance, Fazio and colleagues (2014) observed that the relationship between non-symbolic numerical magnitude comparisons and mathematical competencies depended on age, with the correlation being stronger in children younger than 6 years than in older children, adolescents and adults. Furthermore, Ansari and Holloway (2009) indicated that the association between math skills and the symbolic numerical distance effect existed mainly in the 6-year-olds, but was already diminished by 8 years of age.

Alongside age, discrepancies regarding the relationship between the SNARC effect and math skills might also result from differences in the specific tests used to assess math competencies. According to the meta-analysis by Schneider et al. (2016), the choice of mathematical outcome measure affects the relation between basic numerical skills (as assessed by magnitude comparison performances) and math competencies, with differences between mathematical tasks explaining as much as 14% of the variance of effect sizes (see Holloway & Ansari, 2009).

At any rate, and notwithstanding the fact that inconsistencies between studies could be explained by differences in the study population or assessment methods or both factors, more research is required to understand exactly how inter-individual differences in spatial-numerical mappings relate to more complex mathematical abilities.

5.2.1 Aims of the present study

The present study aimed to determine how number-space associations as indexed by the classically used ***parity SNARC effect*** relate to school-relevant mathematical abilities. Considering that the SNARC effect might be a more appropriate measure for assessing an individual's reliance on spatial-numerical mappings along the MNL than performances on external number line estimation tasks (Schneider et al., 2009), this study should considerably extent our understanding of the specific importance of number-space associations for math competencies in children.

Since the influence of the SNARC effect could potentially depend on the measures used to assess math performances (see e.g., Holloway & Ansari, 2009; Sasanguie et al., 2013; Schneider et al., 2016), the present study assessed mathematical skills using the "Heidelberger Rechentest" (HRT), which is a standardized German math test for elementary school children focussing on two distinct mathematical domains, namely ***arithmetical and visuospatial math abilities***.

Moreover, given the potential influence of participants' ***age***, we not only tested how the parity SNARC effect globally relates to arithmetical and visuospatial math performance, but we also analysed whether and how age affects the relationship between children's number-space associations and math skills. Our study focussed on the 3rd cycle of primary school (corresponding to grade 3 and 4 of the German elementary school system) for two reasons. First, this is the period around which the parity SNARC effect firstly emerges, at least in American and European pupils (Berch, Foley, Hill, & Ryan, 1999), as opposed to Chinese children who already feature a parity SNARC effect as early as Kindergarten (Yang et al., 2014). Moreover, a shift from procedural quantity-based calculation strategies towards more verbal retrieval mechanisms is thought to take place around grade 4 (Van de Weijer-

Bergsma, Kroesbergen, & Van Luit, 2015; see also Imbo & Vandierendonck, 2007; McKenzie, Bull, & Gray, 2003; Prado, Mutreja, & Booth, 2014). Therefore, we reasoned that if the relation between the SNARC effect and mathematical abilities depends on age (and any age-related changes in problem solving strategies), the potential moderating effects of age should be most pronounced in children at this particular developmental stage.

We hypothesized that the children's performances in the standardized math test relate to their number-space associations, but we expected that the strength of this relation might be affected by the mathematical domain that is being assessed, by the children's age, or by both of these factors.

5.3 Methods

The study was approved by the local Ethics Review Panel (ERP).

5.3.1 Participants

A total of 68 children participated in this study. Pupils were recruited from the "3rd cycle" (corresponding to grade 3-4 of the German school system) of two different public elementary schools in Esch-sur-Alzette, Luxembourg. Parents' informed consent was obtained prior to the start of the study, and all children participated voluntarily. Participants came from various backgrounds including different mother languages, of which Luxembourgish and Portuguese were the most common. Roughly two third of the participants had a single mother tongue, while the remaining children were exposed to more than one language at home. Nonetheless, all participants had good comprehension of Luxembourgish and/or German. None of the children suffered from any learning difficulties like dyscalculia, dyslexia, and/or dyspraxia.

Children for whom descriptive information was missing (*N* = 1) or who did not yet fully understand the concept of parity since they asked for assistance while attempting to complete the parity judgment task and/or committed more than 25% of errors on this task (*N*

= 10) were removed prior to data analyses. This reduced the study sample to 57 participants. Among these children, two were additionally excluded since their parity SNARC effects fell 2.5 standard deviations (*SD*) below or above the mean parity SNARC regression slope (for a similar exclusion procedure with adults, see Georges, Hoffmann, & Schiltz, 2016). All analyses were thus conducted on 55 healthy elementary school children for whom descriptive information is displayed in Table 1.

Table 1. Descriptive information for *N* = 55

Variable	Participants
Gender (f/m)	26/29
Handedness (r/l)	49/6
Age (years)	9.5 (*SD* = 0.75, range: 8.35 – 11.37)
HRT arithmetical score (%)	49.17 (*SD* = 11.5, range: 25 – 74.58)
HRT visuospatial score (%)	49.26 (*SD* = 7.69, range: 31.99 – 65.48)
Parity SNARC effect (slope)	-11.37 (*SD* = 16.65, range: -53.01 – 25.95)
Parity judgment RT (ms)	888 (*SD* = 228, range: 616 – 1834)

5.3.2 Procedure and tasks

The tasks were administered during two different testing sessions, which were run on separate days to prevent any possible effects of fatigue. The first testing session comprised paper-and-pencil tests and questionnaires administered collectively in class during approximately 120 min. The second testing session included computerized tasks (programmed in E-prime version 2.0 and administered using a Lenovo ThinkPad). These were completed collectively in groups of 5-6 children over approximately 60 min. The time between sessions depended on the teachers' and children's availabilities and was on average 5.96 weeks (*SD* = 3.66, range 1-11).

Since the present study was conducted in the context of a larger project, a battery of different tests and questionnaires was implemented during the two testing sessions. Only those experiments required to answer the current research questions will be mentioned here and described in more detail below. The Heidelberg Mathematics Test (Heidelberger Rechentest, HRT 1-4, Haffner, Baro, Parzer, & Resch, 2009) was administered during the first testing session, while the parity judgment task was performed during the second testing session. Explanations for both tasks were given in Luxembourgish and German.

5.3.2.1 The Heidelberg Mathematics Test

The Heidelberg Mathematics Test (Heidelberger Rechentest, HRT 1-4, Haffner et al., 2009) was used to assess *mathematical competencies*. It is a standardized speeded math test battery for primary school children in Germany, consisting of two subscales that evaluate different mathematical components. All subtests within each subscale started with a couple of practice items. After completion of the practice trials, children had 2 min to complete each of the subtests.

The *arithmetical ability subscale* comprises six subtests: mental addition (e.g., 17 + 15 = _), mental subtraction (e.g., 50 – 14 = _), mental multiplication (e.g., 6 x 7 = _), mental division (e.g., 28 ÷ 4 = _), number equations filling (e.g., 4 + _ = 3 + 7) and number comparison (e.g., 2 + 9 _ 20). Trials in each subtest were presented serially with an order of increasing difficulty.

The *visuospatial ability subscale* consists of five subtests. In the length estimation subtest, children were required to estimate the length (i.e., number of steps) of a series of two-dimensional black lines by comparing each line with three one-dimensional bolder black lines presented on the top of the test sheet corresponding to 1, 5 or 10 steps respectively. In the object counting subtest, children were instructed to count the number of small objects included in each of 21 presented frames. In the cubes counting subtest, children had to indicate the number of cubes constituting a three-dimensional figure. In the number sequences subtest, children had to complete number sequences (e.g., 1 2 1 2 1 2 _ _ _) by applying a rule established through deductive reasoning. In the connecting numbers subtest, numbers from 1 to 20 were randomly presented in each of 10 frames and participants were required to connect the numbers in their increasing order.

Data analysis and descriptive information

Children received one point for every correctly solved item. Sum scores of arithmetical and visuospatial abilities were then computed across all six arithmetical and five visuospatial subscales subtests respectively and expressed as percentage accuracies. Performances did not differ between the two ability subscales ($F(1, 54) = 0.01$, $p = .95$, ηp2 = .00, see Table 1).

5.3.2.2 The parity judgment task

The parity judgment task was used to assess number-space associations (i.e., the SNARC effect). Children were required to indicate whether a centrally presented single Arabic digit (1-9, excluding 5) was odd or even by pressing the “A” or “L” key on a QWERTZ keyboard respectively. This stimulus-response mapping was reversed for all children in a second block. Trial sequence was identical for all participants, but pseudo-randomized in a way that no digit could appear twice in a row, and the correct response could not be on the same side more than three times consecutively. For a more detailed description of this task see Georges et al. (2016).

Data analysis and descriptive information

Data from the training sessions was not analysed. The mean error rate across all 55 children on experimental trials was 3.55%. Errors were not further analysed. Reaction times (RTs) shorter or longer than 2.5 *SD* from the individual mean were considered as outliers and removed prior to data analysis (2.96%).

Number-space associations were determined using the individual regression equations method (Fias, Brysbaert, Geypens, & D’ Ydewalle, 1996), which provides a single SNARC effect value for each participant. First, RTs were averaged separately for each digit and each response side (left/right) for every participant. Individual RT differences (dRTs) were then calculated by subtracting for each digit the mean left-sided RT from the mean right-sided RT. Subsequently, dRTs were submitted to a regression analysis, using the magnitude of individual digits as predictor variable. Unstandardized regression slopes were taken as a measure of the SNARC effect. Negative regression slopes reflect number-space associations in the expected direction, with a more negative slope corresponding to a stronger SNARC effect. The SNARC effect was significant at the group level, since unstandardized regression slopes significantly differed from zero ($t(54) = -5.07$, $p < .001$, see Table 1).

Individual *parity judgment RTs* were determined by averaging response times across all trials included in the analysis for each participant (see Table 1).

5.3.3 Statistical analyses

First of all, we conducted *correlation analyses* to determine the relationship between all included variables.

Next, two separate *multiple linear regression analyses* were performed on either HRT arithmetical or visuospatial subscale scores including the parity SNARC effect, parity judgment RTs and age as independent variables. This will inform us about the strongest predictor of each subscale.

Finally, two *simple moderation analyses* were performed using Hayes' PROCESS macro for SPSS to investigate whether the relation between the parity SNARC effect and each of the HRT subscale scores was conditional upon age. Moderation will be depicted by the significant effect of the product term between the parity SNARC effect and the moderator variable age on the HRT subscale score, while controlling for the effects of the two factors included in the product term. Parity judgment RTs were also included as covariate in each moderation analysis. A bootstrapping approach with 10.000 bootstrap samples was used for the analysis. Significance was determined at 95% bias-corrected confidence intervals. To avoid multicollinearity issues, all variables were mean centered prior to analyses. Only unstandardized regression coefficients were reported. The Johnson-Neyman computational technique was used to identify the values of the moderator for which the parity SNARC effect and the different HRT subscale scores showed a significant association. This technique identifies the value(s) within the measurement range of the moderator, where the conditional effect of the parity SNARC effect transitions between not statistically significant to statistically significant.

5.4 Results

5.4.1 Correlation analyses

A significant negative correlation was observed between the parity SNARC effect slopes and the HRT arithmetical ability subscale scores (r = -.28, p = .04, Figure 1a), indicating better arithmetic performances in children with stronger number-space associations. Conversely, no relation was revealed between the parity SNARC effect and the HRT visuospatial ability subscale scores (r = -.07, p = .63, Figure 1b). Moreover, the SNARC effect was not related to age or parity judgment RTs. The latter however significantly correlated with the two HRT ability subscale scores (HRT arithmetical subscale: r = -.37, p = .005, HRT visuospatial subscale: r = -.39, p = .003), which were also positively related amongst each other (r = .46, p < .001). Conversely, only the HRT arithmetical but not visuospatial ability subscale scores correlated with age (HRT arithmetical subscale: r = .41, p = .002, HRT visuospatial subscale: r = .19, p = .18), suggesting better arithmetic skills in older children. Age was also related to parity judgment RTs (r = -.3, p = .03). All correlation coefficients are depicted in Table 2.

Table 2. Correlation analyses				
	2.	**3.**	**4.**	**5.**
1. Parity SNARC effect	-.17	.06	-.28*	-.07
2. Parity judgment RT		-.30*	-.37**	-.39**
3. Age			.41**	.19
4. HRT arithmetical ability				.46***
5. HRT visuospatial ability				

Note. *$p < .05$, **$p < .01$, ***$p < 0.001$.

5.4.2 Multiple linear regression analyses

Two multiple linear regression analyses were conducted on either HRT arithmetical or visuospatial ability subscale scores including the parity SNARC effect slopes, parity judgment RTs and age as predictor variables. The regression model on HRT arithmetical ability was significant (R^2 = .36, F(3, 51) = 9.64, p < .001). The parity SNARC effect significantly predicted HRT arithmetical ability subscale scores (b = -0.25, t(51) = -3.13, p = .003) even after controlling for the effects of parity judgment RTs and age, which were also significant predictors of arithmetic performances (see Table 3).

A significant effect could also be observed for the regression model on HRT visuospatial ability (R^2 = .18, F(3, 51) = 3.62, p = .02). The latter ability was however only significantly predicted by parity judgment RTs (b = -0.01, t(51) = -2.89, p = .006). No predictive effect could be observed for the parity SNARC effect (b = -0.07, t(51) = -1.08, p = .29) or age even when partialling out the effects of the remaining variables included in the regression model (see Table 4). Number-space associations, as indexed by the parity SNARC effect, thus explained variance in children's arithmetical, but not in their visuospatial math abilities.

Table 3. Multiple linear regression analysis on the HRT arithmetical ability subscale scores

Model	*b*	*SE-b*	ß	*t*	*p*
Constant	12.06	19.45		.62	.54
Parity SNARC effect	-.25	.08	-.36	-3.13	.003
Parity judgment RT	-.02	.01	-.33	-2.81	.007
Age	5.19	1.81	.34	2.87	.006

Note. R^2 = .36, adj. R^2 = .32, $F(3, 51) = 9.64$, $p < .001$.

Table 4. Multiple linear regression analysis on the HRT visuospatial ability subscale scores

Model	*b*	*SE-b*	ß	*t*	*p*
Constant	52.67	14.79		3.56	.001
Parity SNARC effect	-.06	.06	-.14	-1.08	.29
Parity Judgment RT	-.01	.01	-.39	-2.89	.006
Age	.80	1.38	.08	.58	.57

Note. R^2 = .18, adj. R^2 = .13, $F(3, 51) = 3.62$, $p = .02$.

5.4.3 Simple moderation analyses

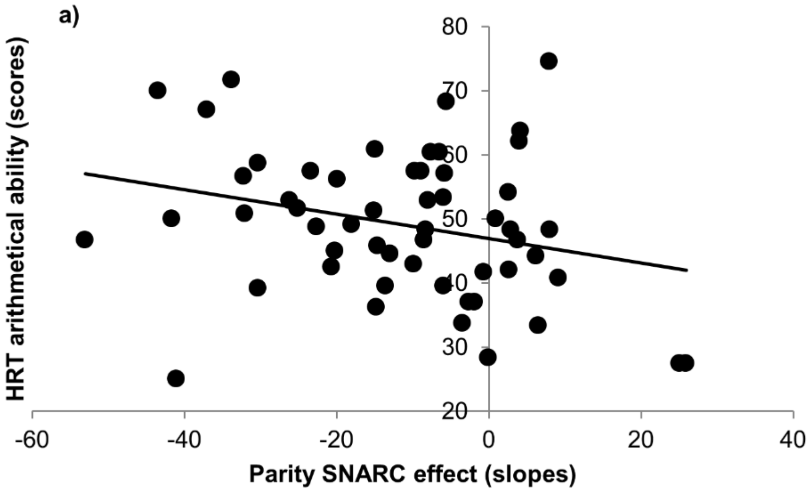
Finally, we tested whether the aforementioned significantly negative relationship between the parity SNARC effect and HRT arithmetical ability subscale scores observed at the population level was moderated by age. In addition, we also determined whether age could possibly moderate the relation between the parity SNARC effect and HRT visuospatial ability subscale scores. Despite the lack of evidence for a significant relation between visuospatial ability and number-space associations in the entire study sample, an association might still be evidenced in some children depending on their ages.

We calculated an interaction term between the parity SNARC effect slopes and age and evaluated whether this interaction term significantly predicted either HRT arithmetical or visuospatial ability subscale scores, while controlling for the variables included in the product term. Parity judgment RTs were also included as covariate in each moderation analysis.

Moderation analysis revealed that the interaction between the parity SNARC effect and age accounted for a significant proportion of the variance in HRT arithmetical ability subscale scores (ΔR^2 = .07, *b* = 0.26, *t*(50) = 2.51, *p* = .02, Figure 2a), when controlling for the effects of the parity SNARC effect, age and parity judgment RTs. Age thus significantly moderated the relationship between number-space associations and arithmetical ability. In general, a significantly negative relation could be observed in the younger children aged 8.75 years (and younger), corresponding to an age of one *SD* below the mean age (*b* = -0.39, *t*(50) = -4.14, *p* < .001, Figure 3). This negative association was slightly less pronounced but still significant in children aged 9.5 years, equivalent to the mean age of the present study sample (*b* = -0.2, *t*(50) = -2.58, *p* = .01, Figure 3). Conversely, no relation between number-space associations and arithmetic performances could be observed in the older children at the age of 10.25 years (and older), representing an age of one *SD* above the children's mean age (*b* = -0.004, *t*(50) = -0.03, *p* = .98, Figure 3). According to the Johnson–Neyman technique, the transition in significance of the conditional effect of the parity SNARC effect on HRT arithmetic ability occurred at the age of 9.63 years. Roughly 62% of the pupils (i.e., 34 children) were younger than this critical value and thus featured significant associations between the parity SNARC effect and HRT arithmetical ability subscale scores.

On the other hand, moderation analysis on HRT visuospatial ability subscale scores did not reveal a significant effect of the interaction term between the parity SNARC effect slopes and age, when controlling for the variables included in the product term and parity judgment RTs (ΔR^2 = .01, *b* = -0.07, *t*(50) = -0.87, *p* = .39, Figure 2b). This thus suggests that the relation between number-space associations and visuospatial math abilities was not conditional upon age.

Figure 1. The relation between the parity SNARC effect and HRT arithmetical (a) and visuospatial (b) abilities



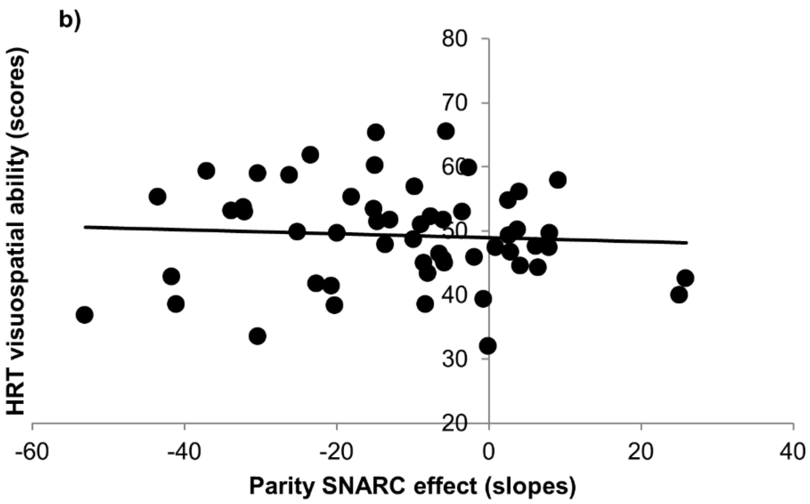


Figure 2. Simple moderation analyses outcomes for HRT arithmetical (a) and visuospatial (b) abilities

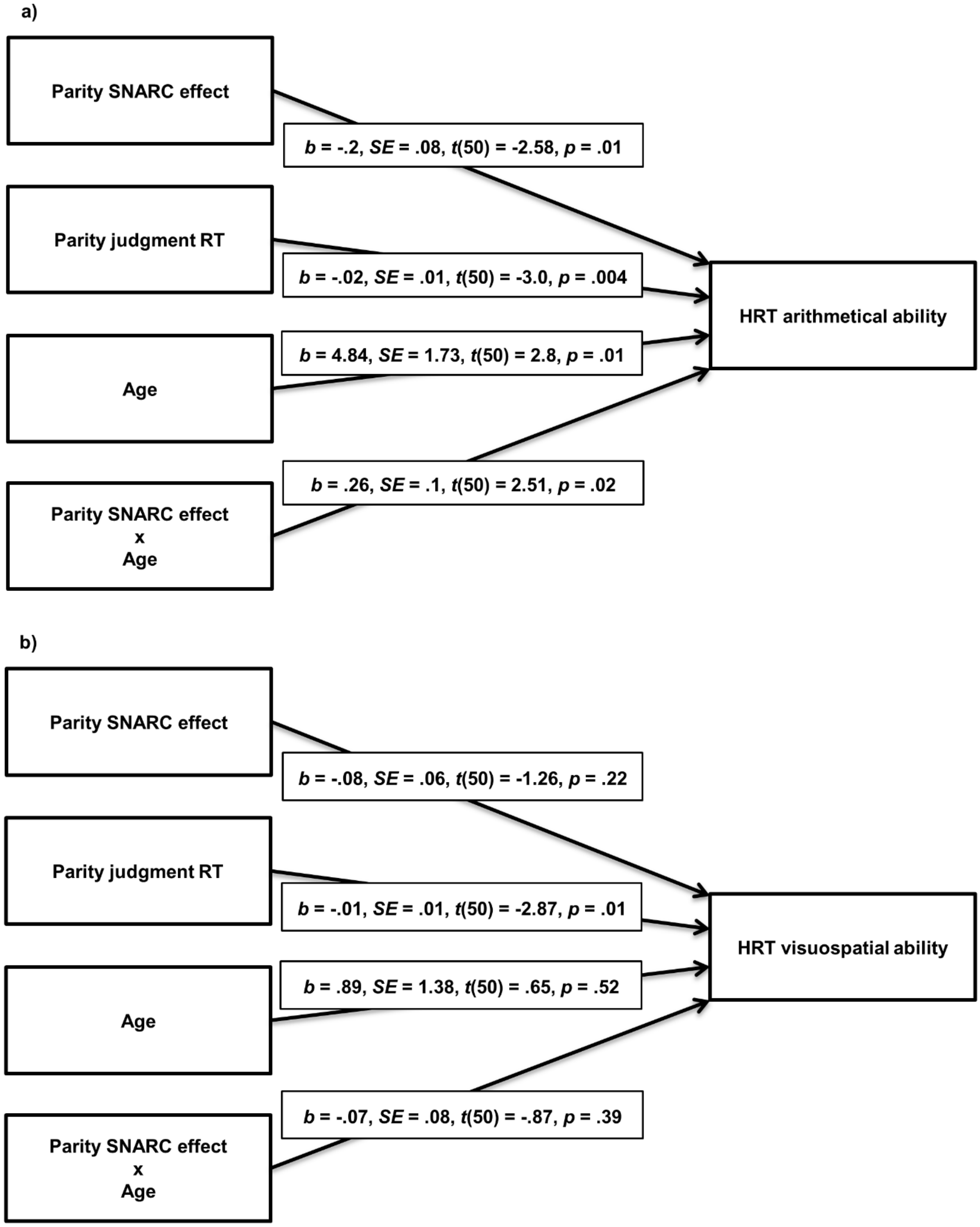
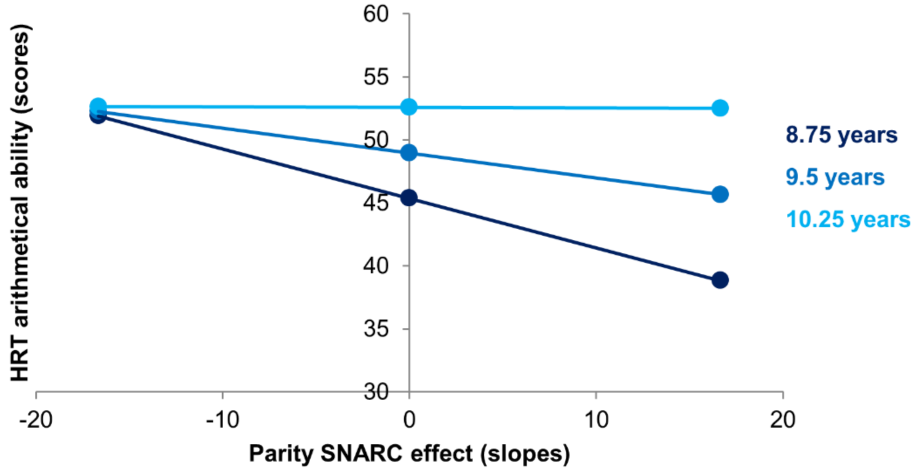


Figure 3. The relations between the parity SNARC effect and HRT arithmetical ability at the mean age (9.5 years) and at -/+ one SD (8.75 and 10.25 years)



5.5 Discussion

The present study used the SNARC effect observed during parity judgments to assess the quality of the children's spatial-numerical representations and to explore how it explains their mathematical competencies. Considering that relations between basic numerical skills and math abilities can change depending on the mathematical domain (e.g., Holloway & Ansari, 2009; Sasanguie et al., 2013; Schneider et al., 2016), we administered a standardized German math test assessing two distinct mathematical components, namely arithmetical and visuospatial math abilities. Moreover, since mathematical skills and the underlying representations rapidly evolve during elementary school (Lyons, Price, Vaessen, Blomert, & Ansari, 2014), we determined whether potential relations between the SNARC effect and more complex arithmetical and visuospatial math abilities depended on age.

5.5.1 Number-space associations relate to arithmetical but not visuospatial math abilities

A significant relation was observed between stronger parity SNARC effects and better *arithmetical skills* as assessed using the arithmetical ability subscale of the HRT math test. This relation remained even after controlling for numerical processing speed as indexed by parity judgment RTs. Conversely, no relation was observed between the parity SNARC effect and *visuospatial math skills* as assessed using the visuospatial ability subscale of the HRT math test.

Such differential effects depending on the mathematical domain not only provide a potential explanation for the previously reported inconsistencies regarding the relation between the SNARC effect and more complex mathematical abilities in adults (e.g., Cipora & Nuerk, 2013 versus Hoffmann et al., 2014), but are also clearly in line with the results summarised in the meta-analysis by Schneider et al. (2016). According to their findings, the choice of mathematical measure affects the relation between basic numerical skills and math performances, with differences between mathematical tasks explaining as much as 14% of the variance of effect sizes. In line with the present results, symbolic magnitude comparison skills related most strongly to mental arithmetics as opposed to curriculum-based measures assessing a wider variety of mathematical skills and therefore possibly also including tasks requiring visuospatial processing.

Interestingly, the present results imply that arithmetical and visuospatial math components depend on distinct cognitive mechanisms, with only performances in the arithmetical subdivision relying on the strength of number-space mappings. This finding is supported by studies showing that arithmetics (and especially subtractions) depend primarily on online calculations using a spatially organized MNL (e.g., Dehaene & Cohen, 1995; Geary, Frensch, & Wiley, 1993). Moreover, Link et al. (2014) reported that the relation between number line estimation performances and mathematical skills was most pronounced for additions and subtractions, possibly because these operations rely on calculations involving a MNL rather than verbal memory retrieval. Further evidence for a MNL-based strategy during arithmetic problem solving (notably additions and subtractions) is provided by the operational momentum effect. This phenomenon describes the observation that individuals systematically over- and underestimate the results of additions and subtractions respectively (e.g., Knops, Viarouge, & Dehaene, 2009; McCrink, Dehaene, & Dehaene-Lambertz, 2007; Pinhas & Fischer 2008), probably because they shift their attention too far along the MNL in the direction of the arithmetic operation. In addition, Knops, Thirion, Hubbard, Michel, and Dehaene (2009) reported that solving additions was related to neural activity associated with rightward saccades, probably due to rightward attentional shifts along the MNL towards larger numbers.

In contrast to arithmetic problem solving, the present results suggest that visuospatial math performances do not depend on the properties of the MNL (at least in 3rd to 4th grade elementary school children). Unfortunately, knowledge about the processes actually contributing to the resolution of visuospatial reasoning problems in math (e.g., geometric tasks) is still very limited. Moreover, no single cognitive construct seems to underlie the completion of such visuospatial tasks, since the strategies reported during the resolution of these tasks varied considerably between individuals. For instance, Boulter and Kirby (1994) indicated that students from grades 7 and 8 adopted either a holistic or analytic processing strategy when solving geometric transformation tasks of reflections and rotations. The use of both holistic and analytic strategies was also reported during the completion of tasks involving the spatial manipulation of 3D objects (Khooshabeh & Hegarty, 2010). Interestingly, the strategies adopted during the resolution of tasks assessing 3D geometrical thinking were shown to depend on individual differences in cognitive preferences (Pitta-Pantazi, Sophocleous, & Christou, 2014). While spatial-visualizers, who were previously shown to feature more efficient use of spatial-processing resources in the right parietal cortex (Lamm, Bauer, Vitouch, & Gstättner, 1999), mainly adopted analytical processing strategies, object-visualizers who generally rely more efficiently on object processing resources in the lateral occipital complex (Motes, Malach, & Kozhevnikov, 2008), largely depended on holistic processing. Qualitative inter-individual differences in problem solving strategies not necessarily depending on the parietal cortex along with the quality of spatial-numerical mappings along the MNL, might thus explain the lack of correlation between the parity SNARC effect and the visuospatial ability subscale of the HRT math test.

5.5.2 Age moderates the relation between number-space associations and arithmetical math abilities

The relation between number-space associations as indexed by the parity SNARC effect and math competencies not only depended on the mathematical domain, but also varied with age. While a significant correlation was observed between stronger parity SNARC effects and better arithmetical abilities in the relatively younger participants, no such relation became apparent in the older children. The moderating effects of age might thus provide another explanation for the previously reported inconsistencies regarding the strength and direction of the relation between the SNARC effect and more complex mathematical abilities.

Such developmental changes in the relation between basic number skills and math abilities, with stronger associations in the relatively younger children, generally agree with several recent studies (Holloway & Ansari, 2009; Sasanguie et al., 2013; see also meta-analysis by Schneider et al., 2016), indicating stronger correlations between symbolic number comparisons and math competencies in 6-year-old than in 8-year-old children. Furthermore, the present findings are directly in line with the study of Hoffmann et al. (2013), reporting better number knowledge with more pronounced number-space associations in children as young as 5 years. Nonetheless, the current results might contradict the recent observations of Gibson and Maurer (2016), reporting no evidence for a significant relation between the SNARC effect and math abilities in 6- to 8-year-olds. The latter study, however, assessed number-space associations using the magnitude classification task (as opposed to the parity judgment task used in the present investigation) and determined math skills based on performances in the TEMA-3, a standardized math test of early mathematical competencies not necessarily distinguishing between different math components. In addition, the authors did not consider the moderating effects of age, although they controlled for the latter variable in a partial correlation analysis. The absence of a relation between number-space associations and math knowledge evidenced by Schneider and colleagues (2009) is, however, in line with the current findings, considering that these authors tested older children already attending 5th to 6th grade. The present findings about a null effect in the relatively older children also agree with Cipora and Nuerk (2013), who failed to observe systematic associations between the SNARC effect and math competencies in adults (see also Bonato et al., 2007; Bull et al., 2013). Nevertheless, they disagree with the study of Hoffmann et al. (2014), reporting that stronger parity SNARC effects were associated with weaker arithmetic performances in university students.

Differences in arithmetic problem solving strategies at different developmental stages could potentially explain the differential relations between number-space associations and arithmetical abilities in the relatively younger and older children. The present findings suggest that the younger participants in the present sample may have relied on a strategy involving spatial-numerical mappings along the MNL to solve arithmetic problems, while older children probably had shifted towards a different strategy not relying on the MNL. Such strategic changes over the course of development have recently been highlighted by Imbo and Vandierendonck (2007), reporting that younger children relied more on procedural calculation strategies for arithmetic problem solving, whereas older participants depended to a greater extent on verbal retrieval mechanisms. Moreover, McKenzie and colleagues (2003) indicated that arithmetic performances of 9-year-old children were affected by both verbal and visuospatial working memory disruption, while the performances of 7-year-old children was only disrupted by visuospatial interferences, suggesting that both age categories used different types of working memory (i.e., different strategies) to solve arithmetic tasks. In this line, Van de Weijer-Bergsma et al. (2015) reported that the predictive effect of visuospatial WM on math performances (i.e., the use of procedural visuospatial strategies for math problem solving) started to decline in 3rd graders until verbal WM completely took over at the end of grade 4. Furthermore, Prado et al. (2014) observed that the involvement of the temporal lobe during arithmetic problem solving (especially multiplications) increased with age. Similarly, extensive training of arithmetic problems (mostly multiplications) induced an activation shift from the intra-parietal sulcus involved in quantity-based processing to the left angular gyrus near the superior edge of the temporal lobe underlying automatic retrieval mechanisms in adults (Delazer et al., 2003). Likewise, Grabner et al. (2007) reported that highly trained individuals completed arithmetic tasks relying more on verbal strategies associated with the activation of the left angular gyrus, while less trained participants depended more on quantity-based processes in the intra-parietal sulcus and the superior parietal regions, also critically involved in number-space interactions (but see Bloechle et al., 2016). The shift from quantity-based strategies involving the MNL towards verbal retrieval mechanisms with age might thus explain the lack of correlation between the parity SNARC effect and arithmetical abilities observed in the relatively older children. However, since age significantly correlated with arithmetical abilities in the present study, it remains unclear whether the hypothesized shift in arithmetic problem solving strategies is driven by age per se or by the gradual increase in the children's math proficiency.

Nonetheless, the present findings clearly suggest that the ability to map numbers onto space no longer positively relates to arithmetic problem solving at later developmental stages in children. Considering that number-space associations do not facilitate arithmetic performances in older pupils, these individuals might progressively start to inhibit the now irrelevant magnitude-associated spatial code during arithmetic problem solving. Such a link between inhibitory control and number-space associations was documented by Hoffmann, Pigat, and Schiltz (2014), reporting weaker SNARC effects in adults with better inhibition capacities. The suppression of number-space associations in older individuals (who have most likely shifted away from a MNL-based strategy) also agrees with Berch et al. (1999), reporting a less pronounced parity SNARC effect in 6^{th} and 8^{th} graders compared to 3^{rd} and 4^{th} graders. However, the parity SNARC effect and age were unrelated in the present population. The relatively older children in the present sample thus still activated (rather than suppressed) the magnitude-associated spatial code to a similar extent than the younger participants, although it was no longer related to successful arithmetic problem solving.

Thus, it could be that the strength of number-space associations only starts to decline at later development stages, once the newly acquired (probably verbal) strategy has been efficiently adopted. Moreover, the extent to which the magnitude-associated spatial code is suppressed at that stage might depend on the degree to which individuals effectively shifted towards verbal retrieval mechanisms and as such their arithmetic proficiency (e.g., Grabner et al., 2007). In a sort of feedback loop, arithmetic performances might subsequently even benefit from greater suppression of spatial-numerical interactions. Unfortunately, as these are only speculations, a clear cause-consequence relation cannot be deduced at this point. Nevertheless, this proposal agrees with the less pronounced SNARC effects in math experts compared to math controls (Cipora et al., 2015; Hoffmann et al., 2014) and also the negative correlation between better arithmetic skills and weaker number-space associations in university students (Hoffmann et al., 2014). It might also provide an explanation for the stronger SNARC effects in students with math learning difficulties (Hoffmann et al., 2014). For instance, Ashkenazi, Rosenberg-Lee, Tenison, & Menon (2012) reported that children with math learning difficulties failed to show reliable activation of verbal regions in the medial temporal gyrus while solving addition problems, suggesting that their impairments prevented them from moving towards verbally-mediated retrieval (see also De Smedt & Gilmore, 2011; Berteletti, Prado, & Booth, 2014). The reliance on immature visuospatial strategies involving the MNL for arithmetic problem solving and as such the lack of suppression of the magnitude-associated spatial code would then underlie their stronger number-space associations in adulthood.

5.5.3 Limitations and outlook

Several authors argued that the SNARC effect might not arise from spatial-numerical coding along a MNL, but result from the serial position of digits canonically ordered in working memory with positions from the beginning/end of the sequence eliciting faster left-/right-sided responses respectively (van Dijck & Fias, 2011). As such the effect of working memory on the relation between number-space associations and arithmetical abilities requires further exploration. Another alternative view to the MNL hypothesis suggests that the SNARC effect arises from categorical verbal-spatial coding, in that spatial-numerical interactions are the result of an association between the verbal categorical concepts “small” and “left” as well as “large” and “right” (Gevers et al., 2010; Proctor & Cho, 2006). Here we considered the SNARC effect as behavioural evidence for number-space mappings along the MNL, but we should bear in mind that it could also arise from verbal or working memory mechanisms not discussed in the present study.

Assuming that better arithmetic skills resulted from stronger number-space associations, we used the arithmetical ability subscale sores of the HRT math test as dependent variable in the moderation analysis. However, because we did not collect longitudinal data, a reverse relation cannot be fully excluded. This is important to consider given that moderation analysis relies on the existence of causal theory and design (e.g., Wu & Zumbo, 2008). Especially in adults, math competencies might affect the quality of spatial-numerical interactions in that better math skills and greater reliance on verbal retrieval mechanisms might entail stronger inhibition of the spatial codes associated with numerical magnitudes, thereby manifesting in weaker SNARC effects. Training studies should shed further light onto this by determining whether practice-induced ameliorations in math skills can transfer to changes (positive or negative) in the strengths of the parity SNARC effect.

Furthermore, future studies should determine the developmental stage at which the negative association between weaker math performances and stronger number-space associations sometimes reported in university students (Hoffmann et al., 2014, but see e.g., Cipora & Nuerk, 2013) firstly emerges and also whether or not it depends on inhibition capacities. The present study should thus be repeated in adolescents and/or young adults during their last years of schooling.

Finally, one might investigate whether age also moderates the relation between other behavioural markers of basic numerical processing (e.g., the distance effect) and math competencies. Knowledge about the predictive value of behavioural indicators at each stage of math development cannot only shed further light onto the specific strategies used to solve math problems at these different developmental stages, but could also guide appropriate educational interventions for each developmental stage. For instance, the present data suggest that intervention programs focusing on number-space associations might be most beneficial for arithmetic problem solving (as opposed to e.g., geometry) in younger children prior to grade 4.

5.5.4 Conclusion

Stronger number-space associations (as indexed by more pronounced parity SNARC effects) significantly related to better arithmetical but not visuospatial math abilities, but only in the relatively younger elementary school children. These findings might be explained by differences in the strategies used to solve different math tasks at different development stages, with a strategy based on number-space mappings being adopted only for arithmetical tasks at the fairly early stages of math development.

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6 Study 2

How Math Anxiety Relates to Number-Space Associations

Georges, C., Hoffmann, D., & Schiltz, C. (2016)

Georges, C., Hoffmann, D., & Schiltz, C. (2016). How Math Anxiety Relates to Number–Space Associations. *Frontiers in Psychology, 7*, 1401. doi: 10.3389/fpsyg.2016.01401

6.1 Abstract

Given the considerable prevalence of math anxiety, it is important to identify the factors contributing to it in order to improve mathematical learning. Research on math anxiety typically focusses on the effects of more complex arithmetic skills. Recent evidence, however, suggests that deficits in basic numerical processing and spatial skills also constitute potential risk factors of math anxiety. Given these observations, we determined whether math anxiety also depends on the quality of spatial-numerical associations. Behavioural evidence for a tight link between numerical and spatial representations is given by the SNARC (spatial-numerical association of response codes) effect, characterized by faster left-/right-sided responses for small/large digits respectively in binary classification tasks. We compared the strength of the SNARC effect between high and low math anxious individuals using the classical parity judgment task in addition to evaluating their spatial skills, arithmetic performance, working memory and inhibitory control. Greater math anxiety was significantly associated with stronger spatio-numerical interactions. This finding adds to the recent evidence supporting a link between math anxiety and basic numerical abilities and strengthens the idea that certain characteristics of low-level number processing such as stronger number-space associations constitute a potential risk factor of math anxiety.

Keywords: Math anxiety; basic number skills; number-space associations; SNARC effect; working memory.

6.2 Introduction

Math anxiety has been defined as an emotional response evoked in some individuals when dealing with numbers and mathematical problems, ultimately disrupting their performance (Suárez-Pellicioni et al., 2015). The prevalence of math anxiety is much higher than previously assumed with more than 30% of 15-year-old students from "Organization for Economic Co-operation and Development" countries reporting feelings of tension or nervousness when solving math problems in school or at home (OECD, 2013). Considering the importance of mathematics in our highly technological society and thus the potentially far-reaching consequences of math anxiety, it is crucial to get a better understanding of the factors contributing to it to facilitate early identification, prevention, and remediation.

Although it remains largely unclear how math anxiety actually develops, it is generally assumed to have multiple origins, with both social influences and cognitive predispositions playing a role in its development. Moreover, an association between math anxiety and gender is commonly reported, with women featuring greater math anxiety than men throughout their entire schooling period (Devine et al., 2012; Hembree, 1990).

The most commonly studied cognitive variables associated with math anxiety are without a doubt arithmetic performance and working memory (WM) (e.g., Ashcraft and Faust, 1994; Ashcraft and Kirk, 2001; Ashcraft et al., 2007; Passolunghi et al., 2016). Recent evidence, however, suggests that math anxiety not only relates to performance deficits on complex arithmetic tasks, but also concerns ***basic numerical processing*** (Dietrich et al., 2015; Maloney et al., 2010; 2011; Núñez-Peña and Suárez-Pellicioni, 2014). For instance, individuals with high math anxiety (HMA) were shown to differ from their low math anxious (LMA) peers on tasks as simple as enumerating items in the counting range (Maloney et al., 2010). Moreover, HMA individuals displayed stronger numerical distance effects (NDE) in both behavioural (Dietrich et al., 2015; Maloney et al., 2011) and ERP settings (Núñez-Peña and Suárez-Pellicioni, 2014). Maloney and colleagues (2011) considered these findings as evidence for a less precise numerical magnitude representation, i.e., a deficit in the approximate number system (ANS), in HMA individuals. Since Dietrich et al. (2015) did, however, not find a relation between math anxiety and the NDE when using a non-symbolic dot comparison task (i.e., the standard task to measure ANS acuity; De Smedt et al., 2013), but only with performance in symbolic number comparison, they suggested that impairment of the latter comparison processes rather than a less precise ANS might constitute a risk factor for the development of math anxiety. In addition to this, Young et al. (2012) reported that children with HMA showed reduced activity in brain regions known to support numerical processing, such as the dorsolateral prefrontal cortex and posterior parietal lobe, during an addition and subtraction verification task. Moreover, Rubinsten and Tannock (2010) observed a strong relationship between developmental dyscalculia and math anxiety. Altogether, these findings thus suggest that basic numerical deficits likely contribute to the emergence of math anxiety, possibly via compromising the development of high-level mathematical skills (Holloway and Ansari, 2009).

Math anxiety has also been negatively associated with basic non-numerical abilities such as ***spatial skills*** (Ferguson et al., 2015; Maloney et al., 2012), suggesting that the deficits observed in HMA individuals extend beyond numerical activities proper. For instance, Maloney et al. (2012) found a strong negative correlation between math anxiety and the spatial visualization scale of the Object-Spatial Imagery Questionnaire (Blajenkova et al., 2006), comprising no math-related content. Moreover, individuals with HMA performed worse than their LMA peers on the paper-and-pencil mental rotation test (Maloney, 2011). This observation could be replicated by Ferguson et al. (2015) using a different measure. A possible explanation for these findings is that poor spatial abilities prevent optimal math achievement (e.g., Gunderson et al., 2012), thereby leading to the development of math anxiety.

Considering the relationships between math anxiety and deficits in basic numerical (Dietrich et al., 2015; Maloney et al., 2011; Núñez-Peña and Suárez-Pellicioni, 2014) and small-scale spatial skills (Ferguson et al., 2015; Maloney et al., 2012) as well as the recently proposed idea that these factors might be at the origin of math anxiety, the present study aimed to determine whether the quality of spatial-numerical associations might also be a potential risk factor of math anxiety.

During binary classification judgments on single Arabic digits, individuals usually tend to be faster for small/large numbers with their left/right hand respectively. This phenomenon, known as the SNARC (spatial-numerical association of response codes) effect, is considered as behavioural evidence for a tight relationship between numerical and spatial representations, with small/large digits being associated with the left/right side of space respectively (Dehaene et al., 1993). Despite the fact that the SNARC effect has been extensively replicated, its cognitive origin remains debated. The dominant and most traditional visuospatial account is based on the idea that numbers are mentally represented along a continuous left-to-right oriented representational medium (the mental number line) with small/large numbers located on the left/right side of the continuum respectively (Dehaene et al., 1993; Moyer and Landauer, 1967; Restle, 1970). Alternatively, the SNARC effect has been proposed to result from a temporary association of numbers and space to be formed in WM, rather than reflecting a long-term memory representation along a mental number line (Fias et al., 2011; Ginsburg et al., 2014; Herrerra et al., 2008; van Dijck et al., 2009). Accordingly, digits would be stored in WM in their canonical order during numerical tasks, with positions from the beginning/end of the sequence eliciting faster left-/right-sided responses respectively, thereby giving rise to the SNARC effect. Evidence in favor of the latter account was provided by studies showing that the SNARC effect indeed critically depended on the availability of WM resources (Herrerra et al., 2008; van Dijck et al., 2009). Regardless of which theory might prevail, the SNARC effect is affected by great inter-individual variability, which depends amongst others on arithmetic performance (Hoffmann, Mussolin et al., 2014, but see Cipora and Nuerk, 2013), spatial skills (Viarouge et al., 2014), and inhibitory control (Hoffmann, Pigat et al., 2014).

In the present study, we investigated whether math anxiety depends on the strength of number-space associations in the classical parity judgment task (i.e., parity SNARC effect) in university students. Moreover, we assessed the symbolic NDE, basic spatial skills, arithmetic performance, visuospatial and verbal WM, and inhibitory control. Apart from complementing previous observations about the link between math anxiety, arithmetic performance, and executive control as well as extending recent evidence about its association with basic numerical and spatial skills, the study outcomes should reveal for the first time whether math anxiety also relates to the spatial nature of numerical representations. This will shed further light onto the particular characteristics of basic number processing potentially constituting a risk factor of math anxiety. Since stronger SNARC effects were shown to be associated with stronger NDE (Viarouge et al., 2014), lower spatial skills (Viarouge et al., 2014), worse arithmetic performance (Hoffmann, Mussolin et al., 2014), and weaker inhibitory control (Hoffmann, Pigat et al., 2014), which all relate to greater math anxiety, we hypothesized that individuals with HMA should display stronger number-space associations than their LMA peers.

6.3 Methods

6.3.1 Participants

A total of 86 students participated in this study, gave written informed consent and received 30€ for their participation. The study was approved by the Ethics Review Panel (ERP) of the University of Luxembourg. All students were recruited via advertisement through their university e-mail addresses. Since the present experiments were conducted in the context of a larger study examining amongst others the effects of mathematical expertise on number-space associations, students were recruited from different mathematical backgrounds. Half of the students came from study fields with a clear absence of explicit daily number and mathematics use (e.g., social and language studies), while the remaining participants all studied math-related subjects (e.g., mathematics, economics, or engineering). Recruitment within the two different math expertise levels was gender-balanced. Mathematical expertise was, however, not included as a between-subject factor, since it was not part of the aim of the current analyses.

Three participants had to be excluded from the sample due to a diagnosis of either attention-deficit/hyperactivity disorder (ADHD) or dyslexia. None of the 83 remaining participants reported to have any math-related or other learning difficulties and/or neuropsychological disorders. After exclusion of the three participants, outliers were identified for each of the different measures included in this study. A total of 18 participants were removed from the population sample, since their performances fell 2.5 standard deviations (*SDs*) below or above the mean group performances on at least one of these measures. Moreover, two participants were excluded due to a misinterpretation of task instructions. More details on outlier removal can be found in the supplementary material. The 63 remaining participants were assigned to either a low (LMA) or a high math anxiety (HMA) group based on a median-split procedure (Rubinsten et al., 2015; Young et al., 2012). Participants featuring overall math anxiety scores below or above the population median score (Mdn = 50) constituted the former or latter groups respectively. Two participants with math anxiety scores equal to the median value were excluded from analyses. The final sample thus consisted of 61 participants, including 31 LMA and 30 HMA individuals.

6.3.2 Procedure and tasks

The study comprised 12 tests consisting of questionnaires, paper-and-pencil exercises and computerized tasks. All computerized tasks were programmed in E-prime (Version 1.2 or 2.0.8.79) and administered using a Dell Laptop with a 15.6 in. color monitor (1024 x 768 pixels).

Participants were tested individually during two 90 min testing sessions. Sessions were run on separate days to prevent any possible effects of fatigue. The time difference between the two testing sessions was not fixed, so that students could sign up for the sessions according to their preferences (e.g., during their free-time on campus between two lectures). The upper limit of one week between testing sessions was implemented to avoid too much variability in the range of time differences between sessions across participants. Time differences between sessions ranged from 1 day to 1 week in both math anxiety groups.

Considering that we performed correlation and regression analyses, all participants performed the tests in the same fixed order as indicated in Table 1. According to Carlson and Moses (2001), a fixed order is standard practice and advisable in individual differences research, since interpreting correlations from designs in which order has been counterbalanced might be hazardous.[1] In addition to the fixed order of the tests, trial sequences were identical for all participants in every task. However, they were pseudo-randomized in a way that the correct response could not be on the same side more than two or three times consecutively in all the binary classification tasks.

[1]The task order chosen in the present study is justified as follows. The parity judgment task was administered before the magnitude comparison task to prevent the priming of numerical magnitudes prior to completion of the former task. Arithmetic tasks were run on separate days to avoid overstraining participants especially those with high math anxiety. The math anxiety questionnaire was administered last to prevent the potential emphasis of the participants' math anxiety through completion of this questionnaire from interfering with their performances specifically on numerical tasks.

Table 1. Order of the tests and the cognitive variables they assess on testing days one and two				
Order	**Testing day one**		**Testing day two**	
	Test	**Cognitive variable**	**Test**	**Cognitive variable**
1.	OSIQ	Spatial visualization	Incompatibility task	Inhibitory control (IES difference)
2.	Speeded matching to sample task	General processing speed	No grid WM task	Visuospatial WM
3.	Parity judgment task	Parity SNARC effect	Categories subtest of the SON-R 6-40	Reasoning ability
4.	Mental rotations test	Mental rotation	Untimed battery of arithmetic operations	Arithmetic performance (ArithACC)
5.	Digit span subtest	Verbal WM	aMARS	Math anxiety
6.	Magnitude comparison task	Distance effect		
7.	FastMath task	Arithmetic performance (FastMathACC; FastMathRT)		

Note. OSIQ = Object spatial imagery questionnaire; SON-R 6-40 = revised Snijders-Oomen nonverbal intelligence test 6-40; aMARS = abbreviated math anxiety rating scale questionnaire.

6.3.2.1 Abbreviated math anxiety rating scale

Math anxiety was assessed using the abbreviated math anxiety rating scale (aMARS; Alexander and Martray, 1989; Baloğlu and Zelhart, 2007), comprising 25 items. Participants were instructed to report their level of anxiety for each item on a 5-point Likert-scale, with 1 for “not at all anxious” and 5 for “very much anxious”. The math anxiety score for each participant was calculated as the sum of all 25 item-scores. Individual levels of math anxiety could thus range from 25 to 125, with increasing scores reflecting an increased level of anxiety.

6.3.2.2 Parity judgment and magnitude comparison tasks

Number-space associations (SNARC effect) and the *numerical distance effect* (NDE) were calculated in the parity judgment and magnitude comparison tasks respectively.

The design of the parity judgment task was adapted from Dehaene et al. (1993) and is described in more detail in the supplementary material. On each trial, one of eight possible stimuli (1, 2, 3, 4, 6, 7, 8 or 9) appeared centrally. In the first block, participants judged as quickly as possible whether it was odd/even by pressing the ''A''/''L'' key on a QWERTZ keyboard respectively. This stimulus-response mapping was reversed for all participants in the second block. Each digit was displayed nine times per block. Each block started with 12-20 training trials, depending on response accuracy.

The design of the magnitude comparison task was adapted from van Galen and Reitsma (2008). The experiment was identical to the parity judgment task with the exception that participants judged whether the centrally presented digit was smaller/larger than five by pressing the ''A''/''L'' key respectively in the first block. This stimulus-response mapping was reversed for all participants in the second block.

Data from the training sessions was not analyzed. The mean error rate on experimental trials was 2.7% and 1.96% in the parity judgment and magnitude comparison tasks respectively. Errors were not further analyzed. Reaction times (RTs) shorter or longer than 2.5 *SDs* from the individual mean were considered outliers and discarded prior to data analysis (3.03% and 3% of all correct trials in the parity judgment and magnitude comparison tasks respectively). The SNARC effect and the NDE were determined using both the individual regression equations method (Fias et al., 1996) and the repeated measures ANOVA and linear trends method (Pinhas et al., 2012).

The individual regression equations method provides a single numerical value for both the SNARC effect and the NDE for every participant. To determine the SNARC effect, RTs were averaged separately for each digit and each response side (left/right) for every participant.

Individual RT differences (dRTs) were then calculated by subtracting for each digit the mean left-sided RT from the mean right-sided RT. The resulting dRTs were subsequently submitted to a regression analysis, using the magnitude of individual digits as predictor variable. To calculate the NDE, trials were grouped based on the absolute value of the distance to the reference digit 5. Mean RTs were then calculated for each of the four distances (1, 2, 3, or 4) and regressed onto numerical distance for every participant. Unstandardized regression slopes were taken as a measure for both effects. Negative regression slopes indicated a SNARC effect in the expected direction (faster left/right-sided responses for small/large digits respectively) and the presence of a NDE. More negative regression slopes corresponded to stronger effects. To determine whether the SNARC effect and the NDE were significant at the group level, unstandardized regression slopes were tested against zero using a one-sample t-test.

The repeated measures ANOVA and linear trends method was used to determine the SNARC and NDE at the group level. To calculate the SNARC effect, an ANOVA was performed on mean dRTs including magnitude as within-subject variable. However, to avoid biases induced by possible MARC (Linguistic Markedness of Response Codes) effects (left-/right-sided advantages for odd/even digits respectively; Nuerk et al., 2004), RTs were collapsed to an even and an odd digit separately for each response side and each participant (as suggested by Pinhas et al., 2012; Tzelgov et al., 2013) and dRTs were computed for each of the four resulting magnitude categories (i.e., very small [1, 2], small [3, 4], large [6, 7], and very large [8, 9]). To determine the NDE, an ANOVA was conducted on RTs including numerical distance as a within-subject factor. SNARC and NDE were revealed by a significant main effect of magnitude and numerical distance respectively associated with a significant linear trend. Effect sizes of the linear trends provided information about the strengths of the effects.

Split-half reliabilities were calculated for the SNARC and NDE regression slopes using the odd–even method to control for systematic influences of practice or tiring within the tasks.

Trials were odd-even half-split (based on order of appearance) and two regression slopes were calculated separately for each effect in every participant. The correlation coefficients were Spearman-Brown corrected to get a reliability estimates for the entire set of items. Reliabilities (SNARC effect: r = .58; NDE: r = .5) were sufficiently high to allow for subsequent interpretation of correlation and regression outcomes.

6.3.2.3 Mental rotations test and Object-Spatial Imagery Questionnaire

Mental rotation ability was assessed using the 24-item mental rotations test (MRT-A) by Peters et al. (1995). For each item, participants were presented with a target figure and four comparison figures, of which two were rotated versions and two were mirror images of the target figure. Participants had eight minutes to identify the two rotated versions of each target figure. Mental rotation ability (MRscore) was given by the number of items where both rotated versions of the target figure were correctly identified (i.e., maximum score = 24).

Spatial visualization style was determined using the Object-Spatial Imagery Questionnaire (OSIQ) by Blajenkova and colleagues (2006). This is a 30-item questionnaire consisting of 15 spatial scale items and 15 object scale items, assessing spatial visualization and object visualization respectively. Participants were asked to rate each of the items on a 5-point scale with 1 labelled “totally disagree” and 5 labelled “totally agree”. Since we did not have any specific hypotheses regarding the participants’ object visualization style, we only computed average scores for the spatial scale items for every participant (SVscore).

Similar to Kozhevnikov et al. (2010), scores from both tasks were normalized within the population and a composite score was computed as follows: zSpatial = zMRscore + zSVscore. This composite score provided us with a single measure of each participant’s spatial skills and was used for correlation analyses.

6.3.2.4 Untimed battery of arithmetic operations and timed FastMath task

Arithmetic performance was assessed using the untimed battery of arithmetic operations (Rubinsten and Henik, 2005; Shalev et al., 2001), consisting of 20 number facts, 32 complex arithmetic problems, 8 decimal problems, and 20 fractions. As in Hoffmann, Mussolin et al. (2014), we scored 1 point for every correctly solved arithmetic problem and expressed accuracy as a percentage (ArithACC). We also administered the timed computerized FastMath task described in detail by Mussolin and colleagues (2012; see also Hoffmann, Mussolin et al., 2014). The task consisted of 20 additions, multiplications, and subtractions on one- or two-digit Arabic numbers. All participants started with additions and finished with subtractions. We computed the accuracy (expressed as a percentage; FastMathACC) and the mean RT of all correct trials (FastMathRT) for each participant.

To compare our data to Hoffmann, Mussolin et al. (2014), accuracy scores from both tasks and RTs were normalized within the population and a composite score was computed as follows: zArithmetic = zArithACC + zFastMathACC – zFastMathRT. This composite score provided us with a single measure of each participant’s arithmetic performance and was used for correlation analyses.

6.3.2.5 No grid visuospatial WM task

Visuospatial WM was assessed using the grid/no grid WM task developed and described in detail by Martin and colleagues (2008). Participants had to remember the spatial locations of black target crosses, sequentially displayed in a 4x4 pattern. In contrast to Martin et al. (2008), only the no grid protocol was implemented, where the 16 possible spatial locations of the target crosses were not explicitly outlined by a grid. At the end of each trial, a comparison figure appeared, consisting of a configuration of darkened squares in a 4×4 subdivision of the background. Participants had to press the “A”/”L” key on a QWERTZ keyboard if the comparison configuration was in accordance/not in accordance with the spatial locations of the target crosses respectively. WM load increased progressively over 36 trials from three to five target crosses. d prime (d') was used as an index of visuospatial WM and computed for every participant by subtracting the false alarm rate (i.e., the proportion of incorrect responses on "no correspondence" trials) from the hit rate (i.e., the proportion of correct responses on "correspondence" trials).

6.3.2.6 Digit span subtest of the WAIS-III battery

Verbal WM was assessed using the digit span subtest of the WAIS-III battery (Wechsler, 1997). We only administered the backward digit span version. Participants' backward digit span was given by the number of correctly recalled sequences.

6.3.2.7 Incompatibility task

Inhibitory control was assessed using a self-designed incompatibility task described in more detail in the supplementary material. The task consisted of experimental and catch trials. On experimental trials, a horizontal arrow was presented centrally in green/red on a 50/50 basis and pointed to the left/right on half of the trials. Participants had to judge the color of the arrow by pressing the "A"/"L" key on a QWERTZ keyboard for green/red arrows respectively regardless of the pointing direction. If the pointing direction of the arrow and the correct response side were the same/opposed, trials were considered as compatible/incompatible respectively. Catch trials were identical to experimental trials except that a green/red rhombus was displayed centrally instead of the arrow. Participants were instructed not to give a response. Catch trials were included to ensure that participants processed the irrelevant spatial dimension of the arrows before making a response based on their color. Individual error rates were determined for each compatibility condition on experimental trials and on catch trials. Individual mean correct RTs were calculated on compatible and incompatible trials after excluding outliers falling 2.5 *SDs* from the individual means.

6.3.2.8 Speeded matching to sample task

General processing speed was determined using the speeded matching to sample task described in detail by Hoffmann, Mussolin et al. (2014). Each trial consisted of a centrally displayed target shape and two possible solution shapes, displayed below to the left and right. Participants had to identify the solution that was identical to the target as quickly as possible by clicking the “A”/“L” key on a QWERTZ keyboard if it appeared on the bottom left/right respectively. General processing speed was determined by averaging RTs across all correct trials.

6.3.2.9 Revised Snijders-Oomen nonverbal intelligence test 6-40

Reasoning ability was ascertained using the categories subtest of the revised Snijders-Oomen nonverbal intelligence test 6-40 (SON-R 6-40). Each of the 36 items consisted of three target pictures all belonging to a certain category and five option pictures of which two possessed the same categorical features than the target pictures. Participants were instructed to point towards the two option pictures that they would associate with the target ones. Items were scored as correct only if both of the option pictures were correctly identified, yielding a maximum score of 36.

6.4 Results

6.4.1 Group comparisons

According to a Chi-square test of independence, math anxiety groups did not differ in terms of gender ($X^2(1) = 0.14$; $p = .71$). A one-way ANOVA on math anxiety scores ($M = 54.66$; $SD = 20.0$; ranging from 26 to 104) including gender as a between-subject variable did not reveal a main effect ($F(1, 59) = 0.29$; $p = .59$; ηp2 = .01), confirming similar levels of math anxiety across women and men. Furthermore, LMA and HMA individuals did not differ in age ($F(1, 59) = 0.001$; $p = .98$; ηp2 = .0). All descriptive information for the two math anxiety groups can be found in Table 2.

Table 2. Descriptive information for the low and high math anxiety groups

Variable	Math anxiety group	
	Low	High
Gender (f/m)	13/18	14/16
Age (years)	23.3 (3.34)	23.28 (3.02)
Handedness (r/l)	30/1	29/1
Math anxiety (score)	38.19 (6.51)	71.67 (13.95)
Parity SNARC effect (slope)	-6.43 (8.64)	-16.84 (14.52)
Distance effect (slope)	-10.29 (6.83)	-15.06 (11.1)
Mental rotation (score)	14.45 (5.38)	12.7 (5.05)
Spatial visualization (score)	3.05 (0.63)	2.93 (0.65)
ArithACC (%)	93.39 (4.38)	91.17 (6.08)
FastMathACC (%)	92.93 (4.37)	92.47 (5.15)
FastMathRT (ms)	2326 (810)	2687 (1027)
Visuospatial WM (d')	.77 (.15)	.66 (.16)
Verbal WM (backward digit span)	7.13 (1.48)	7.07 (1.84)
Compatible IES (ms)	460 (62)	502 (74)
Incompatible IES (ms)	543 (74)	625 (93)
General processing speed (ms)	466 (79)	500 (119)
Reasoning ability (score)	27.1 (4.61)	26 (4.63)

Note. Standard deviations are shown in parentheses.

6.4.1.1 Basic numerical processing

The mean parity SNARC regression slope across all participants was -11.55 (*SD* = 12.91) and significantly differed from zero ($t(60) = -6.99$; $p < .001$), revealing a significant number-space association at the population level. A two-way ANOVA on the parity SNARC regression slopes including math anxiety group and gender as between-subject variables revealed a main effect of math anxiety group ($F(1, 57) = 11.48$; $p < .001$; $\eta p2 = .17$), with HMA individuals featuring a significantly stronger parity SNARC effect than their LMA peers (HMA: slope = -16.84; *SD* = 14.52 versus LMA: slope = -6.43; *SD* = 8.64; see Figure 1A).

There was no effect of gender and no significant interaction between gender and math anxiety group. A two-way repeated measures ANOVA on mean parity dRTs including magnitude category (very small, small, large, very large) as within-subject variable and math anxiety group and gender as between-subject variables revealed a main effect of magnitude category ($F(3, 171) = 27.05$; $p < .001$; ηp2 = .32) associated with a significant linear trend ($F(1, 57) = 56.95$; $p < .001$; ηp2 = .5), thereby confirming the significant number-space association at the population level. However, most importantly and also in accordance with the aforementioned regression slope analysis, a significant interaction was found between magnitude category and math anxiety group ($F(3, 171) = 6.41$; $p < .001$; ηp2 = .1). In both groups, main effects of magnitude category with associated linear trends were observed (HMA: main effect of magnitude category $F(3, 87) = 21.56$; $p < .001$; ηp2 = .43; associated linear trend $F(1, 29) = 43.48$; $p < .001$; ηp2 = .6 versus LMA: main effect of magnitude category $F(3, 90) = 8.64$; $p < .001$; ηp2 = .22; associated linear trend $F(1, 30) = 16.25$; $p < .001$; ηp2 = .35). HMA individuals, however, featured stronger number-space associations, as indicated by their greater effect size (HMA: ηp2 = .43 versus LMA: ηp2 = .22). As for the regression slope analysis, no other effects and/or interactions reached significance.

The mean NDE regression slope across all participants was -12.64 (*SD* = 9.42) and significantly differed from zero ($t(60) = -10.48$; $p < .001$), indicating a significant distance effect at the population level. A two-way ANOVA on NDE regression slopes including math anxiety group and gender as between-subject variables revealed a main effect of math anxiety group ($F(1, 57) = 4.66$; $p = .04$; ηp2 = .08), with HMA individuals featuring significantly stronger distance effects than their LMA peers (HMA: slope = -15.06; *SD* = 11.1 versus LMA: slope = -10.29; *SD* = 6.83; see Figure 1A).There was no effect of gender and no significant interaction. A two-way repeated measures ANOVA on mean RTs including distance as a within-subject factor and math anxiety group and gender as between-subject variables confirmed a main effect of distance ($F(3, 171) = 40.72$; $p < .001$; ηp2 = .42) associated with a significant linear trend ($F(1, 57) = 114.26$; $p < .001$; ηp2 = .67), again highlighting the presence of a distance effect at the population level. Moreover, analysis revealed a main effect of math anxiety group ($F(1, 57) = 4.4$; $p = .04$; ηp2 = .07), with LMA individuals responding on average faster than their HMA peers regardless of distance (LMA: RT = 479 ms; *SD* = 67 ms versus HMA: RT = 510 ms; *SD* = 65 ms). However, contrary to the regression slope analysis, the interaction between math anxiety group and distance did not reach significance ($F(3, 171) = 2.14$; $p = .1$; ηp2 = .04). There was no main effect of gender and no significant interactions.

6.4.1.2 Spatial skills

The mean MRscore across all participants was 13.59 (*SD* = 5.25; ranging from 3 to 23). A two-way ANOVA on MRscore including math anxiety group and gender as between-subject variables revealed a main effect of gender ($F(1, 57) = 4.81$; $p = .03$; ηp2 = .08), with men reaching a significantly higher score than women (male MRscore = 14.88; *SD* = 4.91 versus female MRscore = 11.96; *SD* = 5.31). There was no main effect of math anxiety group and no interaction (see Figure 1B).

The mean SVscore across all participants was 3 (*SD* = 0.64; ranging from 1.47 to 4.27). A two-way ANOVA on SVscore including math anxiety group and gender as between-subject variables did not reveal any main effects or interactions (see Figure 1B), indicating that groups did not differ in terms of their spatial visualization styles.

6.4.1.3 Arithmetic performance

Mean ArithACC and FastMathACC across all participants were 92.3% (*SD* = 5.36; ranging from 78.75% to 100%) and 92.7% (*SD* = 4.74; ranging from 78.33% to 99.17%) respectively. Mean FastMathRT was 2504 ms (*SD* = 934 ms; ranging from 976 ms to 5322 ms). Three separate two-way ANOVAs on either ArithACC, FastMathACC or FastMathRT including math anxiety group and gender as between-subject variables did not reveal any main effects or interactions (see Figure 1C). The different groups did thus not differ in terms of their arithmetic performance.

6.4.1.4 WM

The mean visuospatial d' value across all participants was .71 (*SD* = .16; ranging from .33 to 1). A two-way ANOVA on d' values including math anxiety group and gender as between-subject variables revealed a main effect of math anxiety group ($F(1, 57) = 6.2$; $p = .02$; ηp2 = .1; HMA: *d'* = .66; *SD* = .16 versus LMA: *d'* = .77; *SD* = .15; see Figure 1D), but no effect of gender or interaction. Results thus suggest that HMA individuals featured significantly worse visuospatial WM than their LMA peers regardless of gender.

The mean backward digit span across all participants was 7.1 (*SD* = 1.65; ranging from 4 to 11). A two-way ANOVA on digit span including math anxiety group and gender as between-subject variables did not reveal any main effects or interaction (see Figure 1D).

6.4.1.5 Inhibitory control

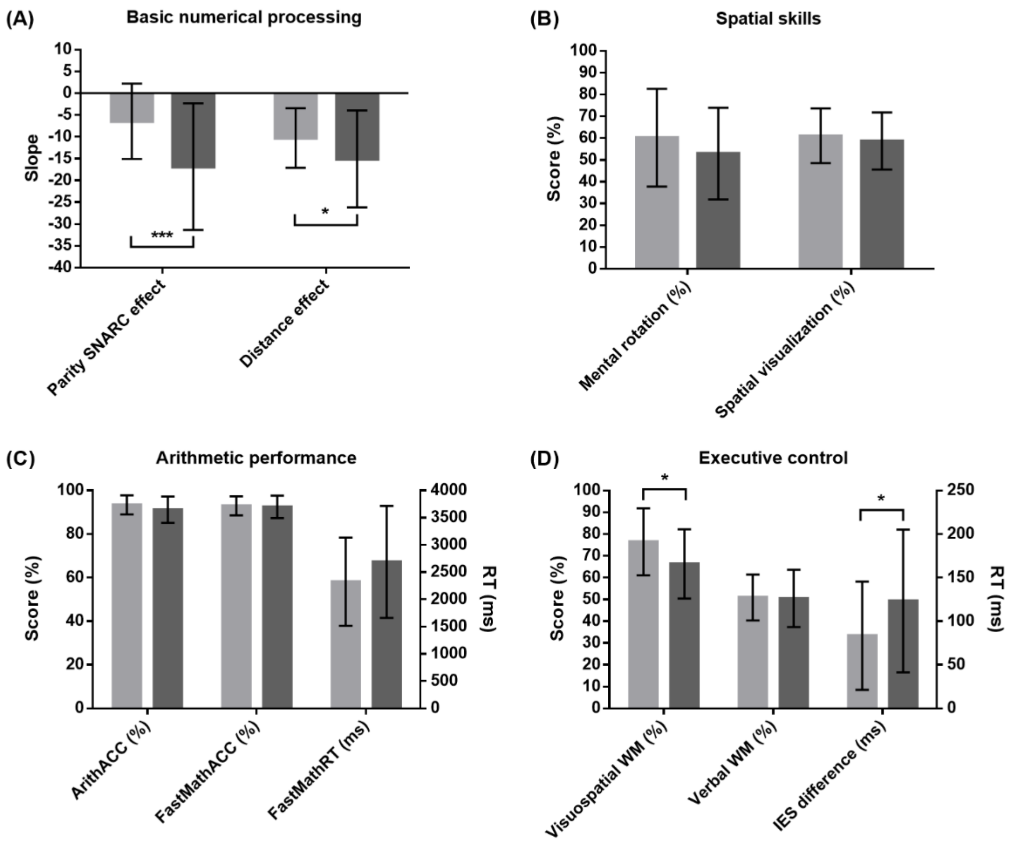
The relatively low overall error rate on catch trials (6.35%; *SD* = 13.23%) suggested that participants attended to the spatial dimension of the target stimuli. A two-way ANOVA on error rates did not reveal any main effects of math anxiety group or gender nor a significant interaction.

The mean error rates and RTs across all participants on experimental trials were 1.23% (*SD* = 2.51%) and 474 ms (*SD* = 65 ms) in the compatible and 6.76% (*SD* = 6.87%) and 540 ms (*SD* = 64 ms) in the incompatible conditions respectively. Error rates and RTs correlated only in the compatible condition (compatible condition: $r = .28$; $p = .03$; incompatible condition: $r = .19$; $p = .15$), suggesting that these performance estimates partly provide different aspects of inhibitory control and that both measures need to be retained for further analyses. To incorporate the two variables into a single performance measure, we computed inverse efficiency scores (IES) by dividing the means of either compatible or incompatible correct RTs by their corresponding percentage accuracies for each participant (Bruyer and Brysbaert, 2011; Khng and Lee, 2014). IES thus adjusts RT performance for sacrifices in accuracy made in favor of response speed. Considering that faster responses together with fewer errors yield smaller IES, the smaller the IES is, the better the performance is.

A repeated measures ANOVA on IES including compatibility condition as within-subject variable revealed a main effect ($F(1, 60) = 116.41$; $p < .001$; ηp2 = .66), highlighting worse performance on incompatible (IES = 583.6 ms; *SD* = 93.03 ms) than compatible (IES = 480.52 ms; *SD* = 71.02 ms) trials at the population level. To get a single inhibitory control measure for each participant, we calculated IES differences by subtracting compatible from incompatible IES. A greater IES difference is indicative of weaker inhibitory control, as it reflects considerably worse performance (i.e., slower RT and/or more errors) on the incompatible compared to the compatible condition. A two-way ANOVA on IES differences including math anxiety group and gender as between-subject variables revealed a main effect of math anxiety group ($F(1, 57) = 4.21$; $p = .05$; ηp2 = .07), with HMA individuals featuring greater IES differences and thus weaker inhibitory control than their LMA peers (HMA: IES difference = 123 ms; *SD* = 82 ms versus LMA: IES difference = 83 ms; *SD* = 62 ms; see Figure 1D). There was no effect of gender and no interaction. IES differences were also used for the subsequent correlation analyses.

6.4.1.6 Other cognitive variables

The mean general processing speed and reasoning ability across all participants were 483 ms (*SD* = 101 ms; ranging from 343 to 861) and 26.56 (*SD* = 4.61; ranging from 14 to 35) respectively. As indicated by two separate two-way ANOVAs, none of these variables differed between HMA and LMA individuals or gender and there was no significant interaction between the independent factors (see Figure 1E). These estimates were mainly included to rule out any differences in general cognitive abilities between the math anxiety groups. Since groups did not differ in these measures and considering that we did not have any specific hypotheses regarding their effects on math anxiety scores, these factors were not considered in the subsequent correlation analyses.



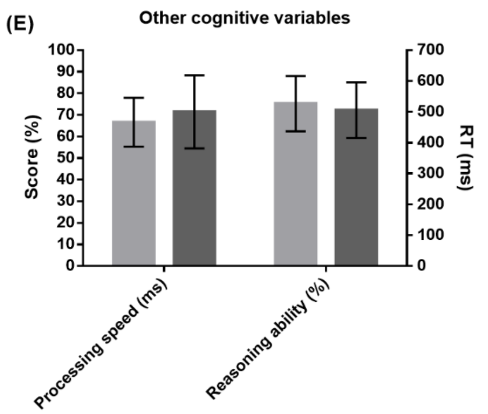


Figure 1. Performances in the low (bright shading) and high (dark shading) math anxiety groups in the tasks probing basic numerical processing (A), spatial skills (B), arithmetic performance (C), executive control (D), and cognitive variables such as processing speed and reasoning ability (E). Score, d' and span values are expressed as percentages of maximum values. Error bars represent standard deviations.* p < .05; ** p < .01; *** p < .001.

6.4.2 Correlation analysis

Despite the tendency of previous studies in the field of math anxiety to run median-splits and divide participants into two (or more) groups based on their math anxiety scores (see e.g., Hopko et al., 1998), we also included the continuous version of this variable for correlation analyses. Considering that performing median-splits is associated with disadvantages such as the loss of information and statistical power (Cohen, 1983), the arbitrary nature of the cut-offs, and the population-dependence of a participant's group membership, additionally running correlation analyses provides us with a clearer and more complete picture of the study outcomes.

All correlation coefficients for *N* = 61 are displayed in Table 3. Similar results were obtained when including the two individuals with math anxiety scores equal to the median value of 50. Correlation coefficients for *N* = 63 can be found in the supplementary material.

A significantly negative correlation was observed between math anxiety scores and the parity SNARC regression slopes (r = -.41; p = .001; see also Figure 2), highlighting greater math anxiety with stronger number-space associations during parity judgments. Math anxiety scores also correlated negatively with the NDE (r = -.31; p = .02), indicating stronger distance effects in individuals with greater math anxiety. Conversely, no significant correlation was revealed between the math anxiety scores and zSpatial (r = -.16; p = .21). This thus further confirms that the level of math anxiety is not related to spatial skills in our population. A significantly negative relationship was, however, revealed between math anxiety scores and zArithmetic (r = -.25; p = .05), although group differences in arithmetic measures did not reach significance. Individuals with lower math anxiety scores thus featured better arithmetic performance. Math anxiety scores also negatively correlated with the d' values of visuospatial WM (r = -.29; p = .02). Conversely, backward digit spans were not related to math anxiety scores (r = -.05; p = .69). These results thus indicate higher math anxiety with weaker visuospatial but not verbal WM. Finally, a positive trend could be observed between math anxiety scores and the IES difference (r = .24; p = .06). This supports the aforementioned significant group difference in this measure, highlighting weaker inhibitory control in individuals with HMA.

Interestingly, the parity SNARC effect and NDE were unrelated (r = .17; p = .19), suggesting that they reflect different properties of basic numerical processing. The parity SNARC effect, however, significantly correlated with zArithmetic (r = .31; p = .02), replicating previous observations about stronger number-space associations in individuals with weaker arithmetic performance (Hoffmann, Mussolin et al., 2014). A significantly positive correlation was also observed between the parity SNARC effect and visuospatial d' values (r = .42; p = .001), highlighting weaker number-space associations in individuals with better visuospatial WM. There was also a tendency for an association between the parity SNARC effect and IES difference (r = -.24; p = .07), indicating stronger number-space associations with weaker inhibitory control (for similar results see Hoffmann, Pigat et al., 2014). The observation that visuospatial and verbal WMs were unrelated (r = .19; p = .15), indicated that they rely, at least partly, on different cognitive mechanisms. Moreover, visuospatial but not verbal WM correlated with zArithmetic (visuospatial: r = .34; p = .01 versus verbal: r = .18; p = .17). zArithmetic was also significantly positively associated with zSpatial (r = .43; p = .001), which in turn correlated with visuospatial WM (r = .26; p = .05).

Including gender as a covariate in a partial correlation analysis did not change any of the aforementioned outcomes. All partial correlation coefficients for N = 61 can be found in the supplementary material.

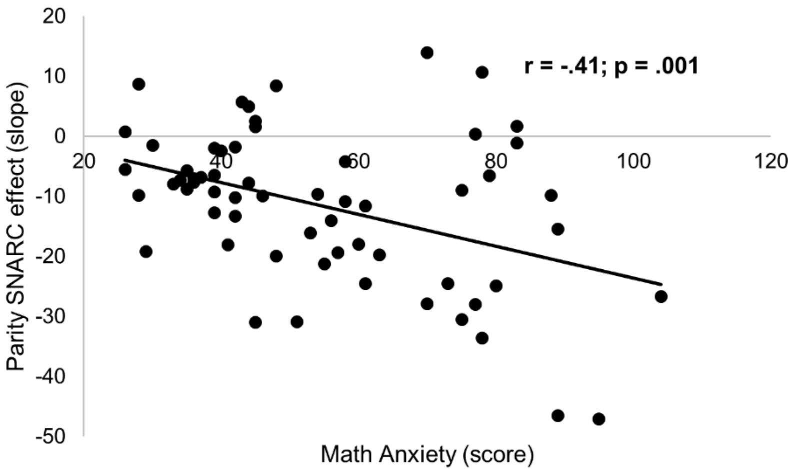
Considering that we performed a large number of correlations, the Holm-Bonferroni method was applied to correct the results for multiple comparisons (Holm, 1979). Since this technique is more powerful than the classical Bonferroni method and maintains the overall rate of false positives without inflating the rate of false negatives unnecessarily, it was the procedure of choice for the present analyses. The relation between math anxiety and the parity SNARC effect remained significant even after applying the Holm-Bonferroni sequential correction (adjusted p value = .03). Significant Holm-Bonferroni adjusted p values are displayed in Table 3.

Table 3. Correlation analysis for *N* = 61

	Parity SNARC effect	Distance effect	zSpatial	zArithmetic	Visuospatial WM	Backward digit span	IES difference
Math anxiety score	**-.41****	-.31*	-.16	-.25*	-.29*	-.05	.24#
Parity SNARC effect		.17	.06	.31*	**.42****	.15	-.24#
Distance effect			.04	.09	-.11	-.02	-.05
zSpatial				**.43****	.26*	.02	-.08
zArithmetic					.34**	.18	.06
Visuospatial WM						.19	-.07
Backward digit span							.13

Note. * p < .05; ** p < .01; *** p < .001; # p < .07. Significant Holm-Bonferroni adjusted p values are displayed in bold.

Figure 2. Correlation between math anxiety scores and the parity SNARC effect regression slopes



6.4.3 Multiple regression analysis

Taking into account the recent findings and theories suggesting that deficits in basic numerical skills contribute to the development of math anxiety and also considering that the main aim of the present study was to determine whether number-space associations are another potential risk factor of math anxiety, we performed stepwise multiple linear regression analysis on math anxiety scores as the dependent variable. In addition to basic numerical skills (i.e., the parity SNARC effect and the NDE), zArithmetic, visuospatial WM and IES difference were included as predictors, since these variables are commonly associated with math anxiety and also correlated with the latter in the present study. This analysis should allow us to determine the best set of predictors of math anxiety. The results will especially inform us about the predictive power of basic numerical skills when controlling for the effects of arithmetic performance and executive control.

The prediction model contained two out of the five predictors and was reached in two steps with no variables removed. The model was statistically significant ($F(2, 58) = 8.51$; $p = .001$) and accounted for approximately 23% of the variance of math anxiety scores ($r = .48$; $R^2 = .23$; adjusted $R^2 = .2$). The parity SNARC effect and the NDE were significant predictors of math anxiety scores, with the parity SNARC effect receiving the strongest weight in the model. The regression outcome thus suggests that math anxiety was primarily predicted by the strength of number-space associations in the parity judgment task and to a slightly lesser extent by the NDE. No additional variance could be explained by arithmetic performance, visuospatial WM or inhibitory control. Raw and standardized regression coefficients of the predictors are shown in Table 4.

Table 4. Stepwise multiple linear regression analysis on math anxiety scores					
Model	***B***	***SE-B***	**ß**	***t***	***p***
Constant	41.49	4.16		9.98	< .001
Parity SNARC effect	-.57	.18	-.37	-3.16	.003
Distance effect	-.52	.25	-.24	-2.08	.04

Note. R^2 = .23; adj. R^2 = .2; $F(2, 58) = 8.51$; p = .001.

6.5 Discussion

Considering recent findings suggesting that deficits in basic numerical processing and spatial skills might be at the origin of math anxiety (Dietrich et al., 2015; Ferguson et al., 2015; Maloney et al., 2010; 2011; 2012; Núñez-Peña and Suárez-Pellicioni, 2014), the present study aimed to determine whether the quality of spatial-numerical associations might also be a potential risk factor of math anxiety. Furthermore, we aimed to replicate the relation between math anxiety and basic numerical and spatial skills, in addition to confirming its well-established associations with arithmetic performance, WM, and inhibitory control.

As hypothesized, we found that greater math anxiety was associated with stronger spatial-numerical interactions in the parity judgment task. This novel finding thus strengthens the assumption that inadequacies in basic numerical abilities might be a potential risk factor of math anxiety. One possible explanation for this association might be that stronger reliance on concrete spatial aspects when dealing with abstract numerical information (as evidenced by stronger SNARC effects) might compromise the optimal development of higher-level mathematical competencies. This, in turn, might put individuals at risk of math failure, subsequently leading to the emergence of math anxiety (see Figure 3A). Of course, this theory relies on the assumption that the parity SNARC effect remains constant throughout development, such that the size of the SNARC effect assessed in university students can be used as an indicator of the strength of their number-space associations during the earlier years of mathematical learning. Support for the idea that stronger number-space associations might cause greater math anxiety via negatively impacting on mathematical performance is provided by recent observations, highlighting a link between stronger spatial-numerical interactions and lower proficiency in the application of basic math knowledge (Hoffmann, Mussolin et al., 2014). Moreover, it is in line with a study on the causal order of math achievement and math anxiety, indicating that prior low math performance related to later high math anxiety across junior and senior high school, but not vice versa (Ma and Xu, 2004).

In general, the idea that inadequate basic numerical skills, such as stronger SNARC effects, might constitute a risk factor for the emergence of math anxiety is in accordance with several observations in the field. For instance, Young et al. (2012) showed that greater math anxiety was associated with altered activity in the posterior parietal lobe already in children as young as first grade, which is a region involved in mathematical reasoning and also the presumed cognitive locus of the SNARC effect (Cutini et al., 2014). Furthermore, Maloney et al. (2011) reported that HMA individuals displayed stronger distance effects (see also Dietrich et al., 2015; Núñez-Peña and Suárez-Pellicioni, 2014, for similar results), which led the authors to suggest that a deficit in the representation of numerical magnitudes (i.e., a defective ANS) might be at the origin of math anxiety. Dietrich et al. (2015) only observed an association between math anxiety and the distance effect in a symbolic, but not in a non-symbolic dot comparison task. They therefore suggested that inadequate numerical comparison processes, rather than weaker ANS acuity (see also van Opstal et al., 2008), might underlie the stronger distance effects in HMA individuals and constitute a risk factor of math anxiety. In line with these findings, Rubinsten and Tannock (2010) observed a strong relationship between developmental dyscalculia and math anxiety.

The link between the symbolic distance effect and math anxiety could also be replicated by the present study. Interestingly, however, we did not find a significant relationship between the NDE and the parity SNARC effect (see Herrera et al., 2008, for similar results; but also see Viarouge et al., 2014), assuming that both phenomena represent different basic numerical competencies whose functional weaknesses predispose individuals to the development of math anxiety. According to these findings, the nature of the numerical inadequacies ultimately leading to greater math anxiety seems to be multi-factorial and heterogeneous.

Although the present study further confirmed the association between math anxiety and basic numerical skills, the recently observed relationship between math anxiety and basic spatial skills such as mental rotation ability and spatial visualization style could not be replicated (Ferguson et al., 2015; Maloney et al., 2012). Considering that the relationship between math anxiety and spatial abilities in the study of Ferguson et al. (2015) was shown to depend on spatial anxiety, differences in this factor and in its association with math anxiety and/or spatial skills in the present population might account for the discrepancy between current and previous findings. Moreover, the present sample was relatively small compared to that of Maloney et al. (2012) and Ferguson et al. (2015) and consisted only of highly educated university students with no general math difficulties or extreme levels of math anxiety. It is possible that a significant correlation between spatial skills and math anxiety might only be evidenced in a larger and broader population including individuals with more variable math anxiety scores and with spatial skills spanning the entire ability spectrum.

The present study could, however, confirm the well-documented negative relationship between math anxiety and arithmetic performance (Ashcraft and Faust, 1994; Ashcraft and Kirk, 2001; Hembree, 1990; Ma, 1999), at least when performing correlation analyses.

We were also able to replicate the association between math anxiety and WM (Ashcraft and Kirk, 2001; Ashcraft and Krause, 2007). The worrying intrusive thoughts associated with math anxiety are thought to consume the limited resources of WM, consequently leading to weaker performance on WM tasks. This has, amongst others, also been suggested as one of the mechanisms through which math anxiety negatively impacts on arithmetic performance (see competition for WM resources theory; Ashcraft and Faust, 1994; Ashcraft and Kirk, 2001; Ashcraft and Krause, 2007). An interesting point worth mentioning here is that the relation between math anxiety and WM could only be evidenced in the visuospatial but not the verbal task. This might seem surprising at first given the numerical content of the backward digit span test. Our results are, however, in accordance with previous findings, assessing the effect of math anxiety on the backward digit span in undergraduate students (Buelow and Frakey, 2013). Ashcraft and Kirk (2001) argued that WM might only be compromised in HMA individuals when the actual math anxiety is aroused, such as in a span task involving computations, since they only evidenced a WM decline in the latter situation. It might thus be possible that despite the numerical content of the backward digit span task, the lack of computations prevented the arousal of math anxiety, thereby explaining the absence of a performance drop in HMA individuals. Conversely, the visuospatial content of the no grid WM task might have been more reminiscent of a mathematical solution, and as such more likely to evoke feelings of anxiety, ultimately compromising WM performance. This might also explain why visuospatial but not verbal WM correlated with zArithmetic.

The link that we observed between math anxiety and inhibitory control also complements previous findings in the literature. For instance, in a numerical Stroop task, HMA individuals needed more time to state the quantity of numerical than non-numerical stimuli, while no difference in RTs could be observed for the LMA group (Hopko et al., 2002). HMA individuals thus seemed to have particular difficulties to focus on task-relevant information in interfering situations. In a similar vein, Pletzer et al. (2015) showed that the compatibility effect in a number comparison task was accompanied by higher neural activity in inhibitory control areas such as the inferior frontal cortex on incompatible trials for LMA but not HMA individuals, again suggesting an inhibitory deficit in the latter group. Finally, in a task where individuals were required to respond to the digits with greater numerical magnitude while ignoring their irrelevant physical size, Suárez-Pellicioni and colleagues (2014) found a greater degree of interference for RTs in the HMA than the LMA group. Hopko et al. (1998) suggested that the greater susceptibility to distraction among HMA individuals and their failure to inhibit attention to the worrying intrusive thoughts associated with math anxiety might be the actual cause underlying their depleted WM and the resulting performance deficits (see deficient attentional control theory).

A final point worth addressing here is that we did not find any gender differences in the level of math anxiety. In addition to this, gender did not interact with math anxiety group nor did it affect correlation outcomes when added as a covariate. While this is in accordance with a number of previous observations (e.g., Birgin et al., 2010; Haynes et al., 2004), it conflicts with other studies, reporting greater math anxiety in women (e.g., Frenzel et al., 2007; Goetz et al., 2013; Hembree, 1990). Gender differences are usually assumed to be driven by confounding factors such as the attitude towards mathematics rather than gender per se (Ashcraft and Ridley, 2005; Beilock et al., 2007). This might be one of the reasons for the absence of gender differences in the present population.

6.5.1 Limitations and outlook

Even though our main hypothesis was based on recent findings and theories suggesting that deficits in basic numerical and spatial skills were at the origin of math anxiety, our correlation and regression results cannot imply a causal relationship and as such it remains unclear whether stronger number-space associations are the causes or rather consequences of high math anxiety. To shed further light onto this, one might for instance determine the effects of experimentally-induced math anxiety (e.g., by exposing women to a stereotyping message regrading better math performance in men) on the strength of the parity SNARC effect.

Although the idea that stronger number-space associations represent a risk factor of math anxiety finds abundant support in the current literature, a reverse association is also easily justifiable. For instance, the decline in math practice often associated with high math anxiety (see global avoidance theory, Ashcraft and Faust, 1994) might entail greater reliance on concrete spatial aspects when dealing with abstract numerical concepts, thereby manifesting in stronger SNARC effects (see Figure 3B). Less trained individuals were indeed shown to have stronger number-space associations than professional mathematicians (Cipora et al., 2015; Hoffmann, Mussolin et al., 2014). Alternatively, the greater susceptibility to distraction in HMA individuals (Hopko et al., 2002; Pletzer et al., 2015; Suárez-Pellicioni et al., 2014) might lead to greater interference of the irrelevant magnitude-associated spatial code during parity judgments, thereby resulting in stronger parity SNARC effects (see Figure 3C). Again, support for this idea is provided by Hoffmann, Pigat et al. (2014), reporting stronger number-space associations with weaker inhibitory control. To demonstrate the validity of the two aforementioned theories, one needs to assess whether math practice and/or inhibitory control actually mediate the relationship between math anxiety and spatial-numerical interactions.

Moreover, future studies should investigate the influence of possible covariates in greater detail. Math practice and/or executive control might for instance be confounding variables in the relation between math anxiety and the SNARC effect, rather than playing a mediating role. Attitude towards mathematics, confidence, and stereotypes could also be considered as potential covariates (Devine et al., 2012).

Furthermore, an extreme group approach (Preacher, 2015) could determine whether spatial skills differ between LMA and HMA groups when including only the lower and upper extremes of the math anxiety distribution (for the implementation of such a design see e.g., Lyons and Beilock, 2011; Maloney et al., 2010; Maloney et al., 2011; Núñez-Peña and Suárez-Pellicioni, 2014).

Finally, since the present study only included highly educated university students with no math difficulties, it needs to be verified whether our main conclusions can hold in a broader and more variable study sample.

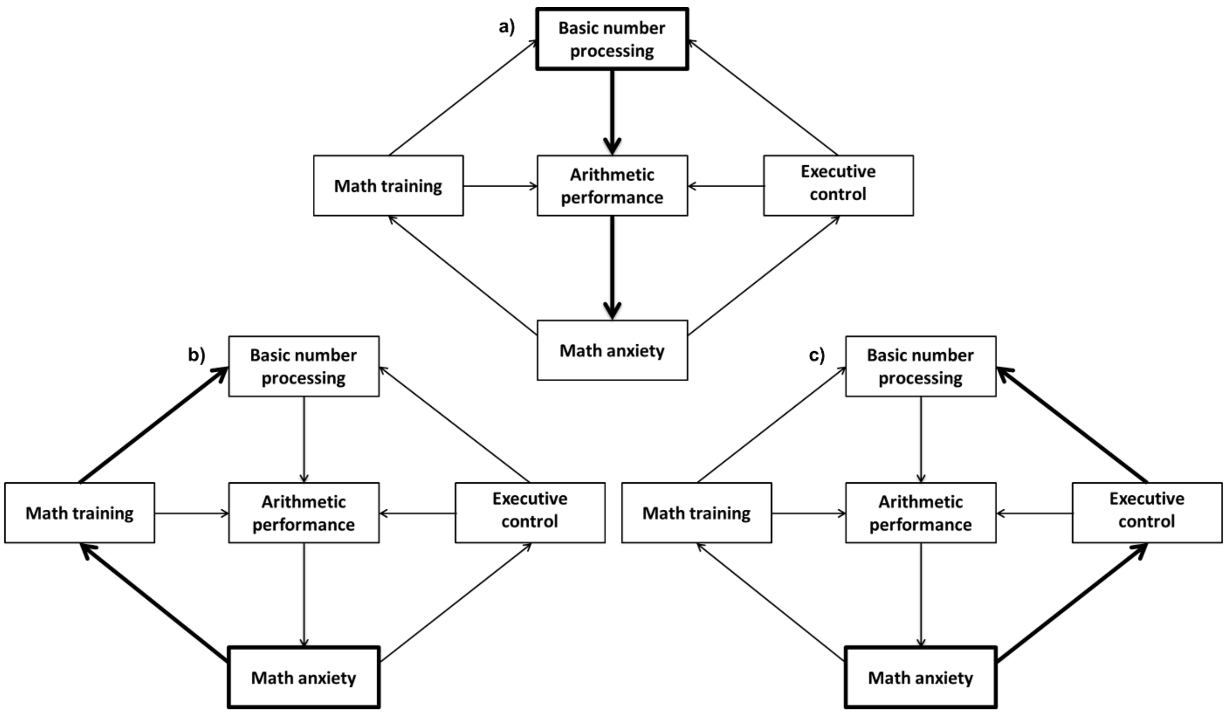


Figure 3. Schematic representations of the different mechanisms potentially accounting for the relationship between math anxiety and basic numerical processing (SNARC effect). Deficits in basic numerical processing lead to math anxiety via weaker arithmetic performance **(A)**. Math anxiety leads to deficits in basic numerical processing via insufficient math training **(B)** or weaker executive control **(C)**. The origin and pathways for each of the different mechanisms are highlighted in bold.

6.5.2 Conclusion

Taken together, the present study showed that greater math anxiety was significantly associated with stronger spatial-numerical interactions in addition to more pronounced distance effects. Moreover, these basic numerical processing skills predicted math anxiety over and above arithmetic performance, WM, and inhibitory control. These findings significantly add to the recent evidence supporting a crucial link between math anxiety and basic numerical abilities and strengthen the idea that deficits in the latter might constitute a potential risk factor of math anxiety (Dietrich et al., 2015; Maloney et al., 2010; 2011; Núñez-Peña and Suárez-Pellicioni, 2014).

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6.7 Supplementary Material

6.7.1 Supplementary methods

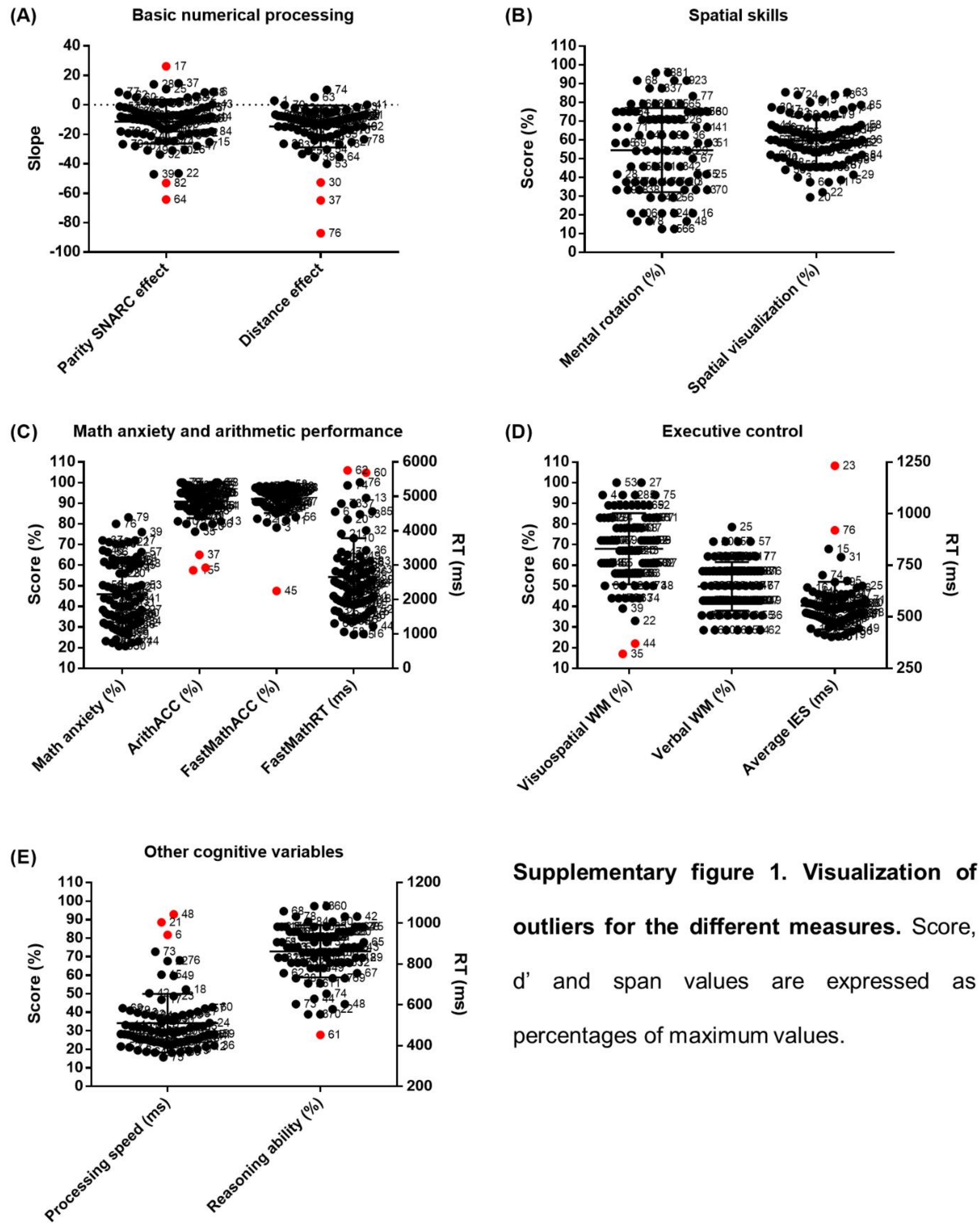
6.7.1.1 Participant exclusion procedure

A total of 86 students participated in this study. Three participants were immediately excluded from analysis due to a diagnosis of either attention-deficit/hyperactivity disorder (ADHD) or dyslexia. After removal of those individuals, outliers were determined for each of the behavioural measures included in this study. If participants' performances fell 2.5 *SDs* below or above the mean group performance on at least one of these measures, they were considered as outliers and excluded from all subsequent analyses. Since many different variables were analyzed for the incompatibility with catch task, we decided to ascertain outliers based on the participants' overall performance on this task (i.e., average IES). A total of 18 participants appeared as outliers (some on more than one measure) and were excluded. The exact number of outliers removed for the different measures can be found in the Supplementary table 1 (see also Supplementary figure 1, for the visualization of outlier performances). In addition to these outliers, two participants were removed from all analyses since they misinterpreted the instructions on the speeded matching to sample task used to assess general processing speed. After the exclusion procedure, the study sample thus consisted of 63 participants. Participants were then assigned to either a low (LMA) or a high math anxiety (HMA) group based on a median-split procedure. Two individuals featured math anxiety scores equal to the median value and were excluded from all subsequent group, correlation and regression analyses. The final study sample therefore comprised 61 participants. Descriptive information for the different populations before and after the exclusion procedure can be found in the Supplementary table 1.

Supplementary table 1. Descriptive information for the different study populations before and after the exclusion procedure and the number of outliers removed for each behavioural measure

Variable	Study population			*N* of outliers
	***N* = 83**	***N* = 63**	***N* = 61**	
Gender (f/m)	40/43	29/34	27/34	/
Age (years)	23.45 (3.06)	23.27 (3.12)	23.29 (3.16)	/
Handedness (r/l)	79/4	61/2	59/2	/
Math anxiety (score)	57.18 (20.08)	54.51 (19.69)	54.66 (20)	0
Parity SNARC effect (slope)	-11.34 (14.98)	-11.65 (12.74)	-11.55 (12.91)	3
Distance effect (slope)	-14.68 (14.24)	-12.73 (9.49)	-12.64 (9.42)	3
Mental rotation (score)	13.08 (5.37)	13.6 (5.2)	13.59 (5.25)	0
Spatial visualization (score)	2.98 (0.63)	2.99 (0.63)	2.99 (0.64)	0
ArithACC (%)	90.81 (8.01)	92.1 (5.45)	92.3 (5.36)	3
FastMathACC (%)	92.1 (6.8)	92.57 (4.74)	92.7 (4.74)	1
FastMathRT (ms)	2660 (1128)	2533 (973)	2504 (934)	2
Visuospatial WM (d')	.68 (.17)	.71 (.16)	.71 (.16)	2
Verbal WM (backward digit span)	6.96 (1.65)	7.08 (1.63)	7.1 (1.65)	0
Average IES (ms)	555 (115)	533 (73)	532 (74)	2
Compatible IES (ms)	501 (111)	481 (73)	481 (71)	/
Incompatible IES (ms)	609 (133)	586 (94)	584 (93)	/
General processing speed (ms)	510 (144)	482 (101)	483 (101)	3
Reasoning ability (score)	26.23 (5.07)	26.37 (4.81)	26.56 (4.61)	1

Note. Standard deviations are shown in parentheses.



Supplementary figure 1. Visualization of outliers for the different measures. Score, d' and span values are expressed as percentages of maximum values.

6.7.1.2 Parity judgment task

The design of the parity judgment task was adapted from Dehaene et al. (1993). The experiment consisted of 144 experimental trials divided equally across two blocks. Each experimental trial started with an empty black-bordered square on a white background (sides

100 pixels, border 2 pixels). After 300 ms, one of eight possible stimuli (Arabic digits 1, 2, 3, 4, 6, 7, 8 or 9) presented in black on a white background in font Arial point size 64, appeared in the center of the black-bordered square and remained for 1300 ms. The inter-trial interval consisted of a blank screen of 1300 ms. Participants had to judge as quickly as possible whether the centrally presented single Arabic digit was odd or even by pressing either the ‘‘A’’ or ‘‘L’’ key on a standard QWERTZ keyboard. In the first block, all participants had to press the “A”/”L” key for odd/even digits respectively. This stimulus-response mapping was reversed for all participants in the second block. Each target digit was displayed exactly nine times per block. The sequence in which the target stimuli appeared was identical for all participants. However, it was pseudo-randomized in a way that no target digit could appear twice in a row, and the correct response could not be on the same side more than three times consecutively. Each block started with 12-20 training trials, depending on response accuracy. If accuracy was at least 70%, participants could directly proceed to the experimental trials after 12 training trials. If the threshold of 70% was not reached, another eight training trials were administered before the experimental trials started. Participants were given a small break half-way through each block.

6.7.1.3 Incompatibility task

To assess inhibitory control, we administered a self-designed incompatibility task, consisting of 32 experimental trials and 8 catch trials. Experimental trials started with the presentation of a black fixation cross in font Courier New point size 18 in the center of a white background. After 400 ms, the fixation cross was replaced by a horizontal arrow that disappeared upon response or after a maximum of 1000 ms. The central arrow was presented in either green or red on a 50/50 basis. Regardless of its color, the arrow pointed to the left on half of the trials and to the right on the remaining half. Participants were instructed to judge the color of the arrow by pressing the “A”/“L” keys on a standard QWERTZ keyboard for green/red arrows respectively regardless of the pointing directions. If pointing direction coincided with correct response side, the experimental trials were considered as compatible. On incompatible trials, correct response side and the pointing direction of the arrow were opposed. The inter-trial interval consisted of a blank screen for 500 ms. Catch trials were identical to experimental trials with the exception that a rhombus was displayed in the center of the screen instead of the arrow. The rhombus appeared in either green or red, but regardless of its color, participants were instructed not to give a response. It disappeared in case of response or after a maximum of 1000 ms. Catch trials were included to ensure that participants processed the irrelevant spatial dimension of the arrows before making a response based on their color. Trial sequence was identical for all participants, but it was pseudo-randomized in a way that the correct response could not be the same more than 2 times consecutively. The actual experiment was preceded by 10 practice trials, consisting of 8 experimental trials and 2 catch trials.

6.7.2 Supplementary results

6.7.2.1 Correlation analyses

Correlation analyses were repeated with $N = 63$. Similar results were obtained regardless of whether the population sample consisted of 61 or 63 participants. Results are displayed in the Supplementary table 2.

Including gender as a covariate in a partial correlation analysis did not change any of the outcomes. All partial correlation coefficients for $N = 61$ are found in the Supplementary table 3.

Supplementary table 2. Correlation analysis for *N* = 63

	Parity SNARC effect	Distance effect	zSpatial	zArithmetic	Visuospatial WM	Backward digit span	IES difference
Math anxiety score	-.41**	-.3*	-.16	-.23#	-.29*	-.05	.21
Parity SNARC effect		.16	.06	.29*	.41**	.15	-.24#
Distance effect			.05	.13	-.08	-.03	.05
zSpatial				.42**	.26*	.02	-.06
zArithmetic					.36**	.18	.09
Visuospatial WM						.19	-.03
Backward digit span							.08

Note. * $p < .05$; ** $p < .01$; *** $p < .001$; # $p < .07$.

Supplementary table 3. Partial correlation analysis for *N* = 61 including gender as a covariate

	Parity SNARC effect	Distance effect	zSpatial	zArithmetic	Visuospatial WM	Backward digit span	IES difference
Math anxiety	-.42**	-.3*	-.15	-.25#	-.3*	-.06	.25#
Parity SNARC effect		.17	.08	.31*	.42**	.14	-.23#
Distance effect			.02	.09	-.11	-.01	-.05
zSpatial				.44***	.31*	.05	-.1
zArithmetic					.35**	.18	.06
Visuospatial WM						.18	-.06
Backward digit span							.13

Note. * $p < .05$; ** $p < .01$; *** $p < .001$; # p < .07.

7 Study 3

How and Why Do Number-Space Associations Co-Vary in Implicit and Explicit Magnitude Processing Tasks?

Georges, C., Hoffmann, D., & Schiltz, C. (under review)

7.1 Abstract

Evidence for number-space associations in implicit and explicit magnitude processing tasks comes from the parity and magnitude SNARC effect respectively. Different spatial accounts were suggested to underlie these spatial-numerical associations (SNAs) with some inconsistencies in the literature. To determine whether the parity and magnitude SNAs arise from a single predominant account or task-dependent coding mechanisms, we adopted an individual differences approach to study their correlation and the extent of their association with arithmetic performance, spatial visualization ability and visualization profile. Additionally, we performed moderation analyses to determine whether the relation between these SNAs depended on individual differences in those cognitive factors. The parity and magnitude SNAs did not correlate and were differentially predicted by arithmetic performance and visualization profile respectively. These variables, however, also moderated the relation between the SNAs. While positive correlations were observed in object-visualizers with lower arithmetic performances, correlations were negative in spatial-visualizers with higher arithmetic performances. This suggests the predominance of a single account for both implicit and explicit SNAs in the two types of visualizers. However, the spatial nature of the account differs between object- and spatial-visualizers. No relation occurred in mixed-visualizers, indicating the activation of task-dependent coding mechanisms. Individual differences in arithmetic performance and visualization profile thus determined whether SNAs in implicit and explicit tasks co-varied and supposedly relied on similar or unrelated spatial coding mechanisms. This explains some inconsistencies in the literature regarding SNAs and highlights the usefulness of moderation analyses for understanding how the relation between different numerical concepts varies between individuals.

Keywords: Parity SNA; magnitude SNA; visualization style; arithmetic performance; individual differences; moderation analysis.

7.2 Introduction

7.2.1 Evidence for number-space associations

An impressive number of studies on numerical cognition hint towards a potential link between numbers and mental space (e.g., Dehaene, Bossini, & Giraux, 1993; Wood, Willmes, Nuerk, & Fischer, 2008). While smaller numbers are generally related to the left side of space, larger numbers are usually associated with the right side of space, at least in Western societies. These spatial-numerical associations (SNAs) have been evidenced across a variety of different contexts involving not only healthy individuals, but also neurologically impaired patients (for a recent review, see Fischer & Shaki, 2014). Interestingly, number-space associations can be observed regardless of whether the numerical task requires the explicit processing of numerical magnitude or not.

For instance, the central display of a non-informative digit was shown to facilitate responses to stimuli in either the left or right hemifield depending on its magnitude (Fischer, Castel, Dodd, & Pratt, 2003). Similarly, participants deviated to the left or right when asked to state the midpoint of a line composed of irrelevant smaller or larger digits respectively (Fischer, 2001). Moreover, individuals usually respond faster to small/large digits with their left/right hand respectively in binary classification tasks not involving explicit magnitude processing, such as during parity judgments (Dehaene et al., 1993) or when evaluating the pointing direction of a shape superimposed on digits (Fias, Lauwereyns, & Lammertyn, 2001; Lammertyn, Fias, & Lauwereyns, 2002; Mitchell, Bull, & Cleland, 2012). The latter phenomenon, known as the SNARC effect (Spatial Numerical Associations of Response Codes; Dehaene et al., 1993) has, however, also been observed during explicit numerical magnitude judgments (Dehaene, Dupoux, & Mehler, 1990; Gevers, Verguts, Reynvoet, Caessens, & Fias, 2006), indicating that number-space associations can be reliably measured regardless of the implicit or explicit nature of the task.

7.2.2 Spatial coding mechanisms underlying number-space associations

Even though number-space associations have been extensively replicated in tasks with implicit and explicit magnitude processing, the cognitive mechanisms contributing to SNAs are highly debated. Up to date, three spatial coding accounts have been suggested to underlie spatial-numerical interactions, including a visuospatial, verbal-spatial, and working memory (WM) account.

The dominant and most traditional *visuospatial* explanation for number-space associations is that numbers are mentally represented along a continuous left-to-right oriented spatial representational medium, also known as the mental number line (MNL), with small/large numbers located on the left/right side of the continuum respectively, at least in Western societies (Dehaene et al., 1993; Moyer & Landauer, 1967; Restle, 1970). However, considering that this coding mechanism implies a systematic, long-term mapping between numbers and space, it might be less suited to account for the flexibility of spatial-numerical interactions (e.g., Bächtold, Baumüller, & Brugger, 1998; Shaki & Fischer, 2008).

An alternative view suggests that SNAs arise from categorical *verbal-spatial* coding. According to the polarity coding account by Proctor and Cho (2006), the stimulus and response alternatives in binary classification tasks are coded as negative and positive polarities, with the congruency between the polar codes on the stimulus and response dimensions facilitating response selection. SNAs would thus arise due to the association of the verbal categorical concepts “small” and “left” with the same (e.g., negative) polarity and “large” and “right” with the remaining (e.g., positive) polarity (see also the neural network model proposed by Gevers, Verguts, Reynvoet, Caessens, & Fias, 2006). However, the drawback of this account is that it is less likely to explain number-space associations evidenced in tasks without lateralized responses such as in random number generation (Loetscher et al., 2008) or digit string bisection tasks (Fischer, 2001).

A final explanation for the link between numbers and space was recently provided by van Dijck and Fias (2011), who argued that spatial-numerical interactions are task-specific associations established within *WM*. Number-space associations, such as the SNARC effect, would arise from the serial position of digits in WM (canonically ordered), with positions from the beginning/end of the sequence being associated with the left/right side of space respectively. Evidence in favor of the WM account was provided by studies showing that the SNARC effect indeed critically depended on the availability of WM resources (Herrerra, Macizo, & Semenza, 2008; van Dijck, Gevers, & Fias, 2009).

Considering the different spatial coding mechanisms proposed to account for number-space associations, the question arises whether only one of these accounts underlies spatial-numerical interactions regardless of the task or whether different spatial coding mechanisms might play a role depending on whether the task requires implicit or explicit processing of numerical magnitudes.

Several findings in the literature suggest that a single spatial coding mechanism predominates in both implicit and explicit magnitude processing tasks. For instance, number-space associations were shown to mainly arise from verbal-spatial coding mechanisms not only in the parity judgment (van Dijck, Gevers, & Fias, 2009), but also in the magnitude classification task in adults and children (Gevers et al., 2010; Imbo, Brauwer, Fias, & Gevers, 2012). In a similar vein, although suggesting the involvement of a different account, Viarouge, Hubbard, and McCandliss (2014) observed a correlation between the parity SNARC effect and mental rotation ability, suggesting the activation of visuospatial processes during implicit magnitude judgments, while van Dijck et al. (2009) highlighted the importance of the visuospatial account in the magnitude SNARC effect, as the latter was selectively abolished by a visuospatial but not verbal WM load. Finally, Cheung, Ayzenberg, Diamond, Yousif, and Lourenco (2015) reported a significant correlation between parity and magnitude SNAs, even when partialling out the effects of general cognitive tasks or participants' RTs, again suggesting the activation of common spatial coding processes in both tasks.

In contrast, the hypothesis that different coding mechanisms might come into play depending on the task assessing number-space associations also receives robust support from the literature. For instance, we recently showed that the spatial mechanisms underlying number-space associations depended on contextual elements such as the task instructions (Georges, Schiltz, & Hoffmann, 2015[2]). Similarly, Ginsburg and Gevers (2015) observed that the association of numerical magnitudes with space in a magnitude classification task was tied to either long-term semantic representations along the MNL or short-term representations temporarily activated in WM depending on whether the magnitude judgment was conditional on a preliminarily memorized numerical sequence or not. Furthermore, number-space associations in the parity judgment and magnitude classification tasks could be selectively abolished by a verbal and visuospatial WM load respectively (van Dijck et al., 2009). Moreover, findings from a principle component analysis showed that SNAs in the parity judgment and magnitude classification tasks were placed in two separate components (van Dijck, Gevers, Lafosse, & Fias, 2012), thus suggesting that spatial-numerical interactions in implicit and explicit magnitude processing tasks potentially arise from qualitatively different cognitive mechanisms. Furthermore, while hemi-neglect patients featured regular spatial-numerical interactions in the parity judgment task, where access to numerical magnitude is implicit, they showed atypical number-space associations in the explicit magnitude classification task (Priftis, Zorzi, Meneghello, Marenzi, & Umilta, 2006; Zorzi et al., 2012). Finally, SNAs were shown to assume a continuous versus categorical shape in the parity judgment and magnitude classification task respectively (Gevers et al., 2006; Wood et al., 2008), thereby further suggesting task-dependent spatial coding mechanisms. Alternatively, such task differences in the shape of SNAs might simply result from different stimulus response latencies depending on the numerical judgment (i.e., parity judgment versus magnitude classification). The categorical shape of number-space associations in magnitude classification tasks might for instance be explained by the fact that reaction times are usually slower for digits closer to the referent than for stimuli further away from the referent (see numerical distance effect), with slower responses subsequently leading to more pronounced number-space associations. SNAs for digits in the intermediate

[2] This article corresponds to study 4 presented in this thesis.

range of the numerical interval would then be as strong as SNAs for stimuli in the extreme range, manifesting in a categorical shape. Nonetheless, the aforementioned findings more readily suggest the contribution of multiple spatial coding mechanisms, whose activational extent depends on task characteristics.

7.2.3 Individual differences in number-space associations

To better understand which spatial coding mechanisms potentially contribute to number-space associations, several recent studies have adopted an individual differences approach by investigating how individual differences in SNAs can be explained by differences in other cognitive processes (e.g., Cipora & Nuerk, 2013; Hoffmann, Mussolin, Martin, & Schiltz, 2014; Hoffmann, Pigat, & Schiltz, 2014; Viarouge et al., 2014).

Variability in the parity SNARC effect has for instance been related to individual differences in mathematical skills. Participants scoring lower in arithmetic measures displayed more pronounced number-space associations in the parity judgment task (Hoffmann, Mussolin, Martin, & Schiltz, 2014; but see Cipora & Nuerk, 2013). Similarly, participants with math difficulties revealed stronger SNAs than math controls (i.e., people not studying math-related topics; Hoffmann et al., 2014), while the weakest parity SNARC effects were evidenced in math professionals (Cipora et al., 2016). In addition, number-space associations in the parity judgment task were shown to relate to spatial visualization ability, such that individuals with weaker mental rotation skills displayed stronger parity SNARC effects (Viarouge et al., 2014).

Interestingly, however, despite these findings associating individual differences in arithmetic and spatial skills with variability in the parity SNARC effect, corresponding investigations using explicit magnitude judgement tasks are lacking. Furthermore, to the best of our knowledge, there are currently no differential psychology studies examining whether individual differences in numerical and spatial factors can influence the extent to which number-space associations co-vary in implicit and explicit magnitude processing tasks.

Another concern is that spatial visualization style, a factor related to both arithmetic performance and mental rotation ability, has never been considered as a potential candidate for explaining individual differences in either parity or magnitude SNAs, let alone the extent of their covariance. Among the object and spatial visualization styles defined in the literature (Kozhevnikov, Kosslyn, & Shephard, 2005), the latter was shown to relate to success in higher mathematics (e.g., Anderson et al., 2008; Kozhevnikov et al., 2005; van Garderen, 2006). Moreover, individuals with high spatial but low object imagery performed considerably better in number sense and algebraic reasoning tasks than participants with low spatial and high object visualization styles or a mixed visualization profile (Chrysostomou, Pitta-Pantazi, Tsingi, Cleanthous, & Christou, 2013). These findings thus emphasize the importance of visualization style in mathematical learning and achievement and suggest that it might also explain individual differences in lower level numerical processing such as number-space associations in implicit and/or explicit magnitude processing tasks.

7.2.4 Aims of the present study

Considering the debate about the spatial nature of the coding processes underlying number-space associations and also the controversy about whether the activation of these mechanisms might depend on explicit or implicit magnitude processing, we first of all aimed to determine whether a significant correlation can be observed between the SNARC effects in the parity judgment and magnitude classification tasks (*aim 1*). Finding evidence for a significant association between both SNAs would suggest the predominance of a single spatial coding account at least at the population level.

Secondly, we investigated to what extent number-space associations in implicit and explicit magnitude processing tasks can be explained by individual differences in numerical and spatial factors (*aim 2*). This will not only advance our understanding of the cognitive mechanisms contributing to each of the SNARC effects at the population level, but also shed further light onto whether spatial-numerical interactions in implicit and explicit magnitude processing tasks arise from similar or unrelated spatial coding mechanisms. An association with the same cognitive factors alludes to the predominance of a single underlying spatial coding account. Conversely, if the parity and magnitude SNARC effects are differentially related to the different numerical and spatial variables, the contribution of task-dependent spatial processes can be assumed. Considering the previously observed associations between the parity SNARC regression slopes and arithmetic performance (Hoffmann, Mussolin et al., 2014; but see Cipora & Nuerk, 2013) as well as spatial visualization ability (Viarouge et al., 2014), both of these measures were included as predictors in the present study. This not only allowed us to determine whether we could replicate the aforementioned relationships, but also gave us the opportunity to evaluate whether these variables relate to number-space associations in tasks with explicit reference to numerical magnitude. Apart from these factors, we also focused on visualization style, considering that it was shown to predict success in higher level mathematics (e.g., Kozhevnikov et al., 2005) as well as achievement in tasks assessing number sense (Chrysostomou et al., 2013). Since performance in numerical tasks varied with both object and spatial visualization styles (Chrysostomou et al., 2013), we contrasted the two visualization styles within each individual and determined in how far visualization profile (i.e., the preference for a certain visualization style) affected number-space associations in implicit and explicit magnitude processing tasks.

Finally, we used moderation analyses to investigate whether individual differences in the aforementioned numerical and spatial factors might not only explain differences in the strengths of the parity and magnitude SNARC effects, but could also determine the extent to which number-space associations in implicit and explicit magnitude processing tasks co-vary (*aim 3*). Finding evidence for a significant association between the two SNAs only in some individuals, but not others, would suggest the predominance of a single coding account in the former, but task-dependent spatial coding processes in the latter.

Overall, this study should advance our understanding of whether number-space associations in implicit and explicit magnitude processing tasks arise from a single account or multiple unrelated spatial coding mechanisms at the population level. Moreover, studying the extent to which the different number-space associations can be predicted by numerical and spatial factors will inform us about the cognitive mechanisms primarily contributing to each of the SNAs in the entire population. This will be especially informative with regard to magnitude SNAs, since their variability has never been investigated using individual differences in cognitive measures. Moreover, with the inclusion of visualization profile, we will extent previous findings about the relationships between number-space associations and arithmetic and spatial variables. Finally and most importantly, this is the first study using moderation analyses to investigate whether individual differences in cognitive variables can determine the relation between number-space associations in implicit and explicit magnitude processing tasks and thus supposedly the relatedness of their underlying spatial coding mechanisms. This should help clarify some of the inconsistencies in the literature regarding the spatial nature of the cognitive processes accounting for number-space associations.

7.3 Methods

The study was approved by the local Ethics Review Panel (ERP).

7.3.1 Participants

A total of 128 participants were recruited via advertisement through their university e-mail addresses, gave written informed consent and received 30€ for their participation. Half of the students came from study fields with a clear absence of explicit daily number and mathematics use (e.g., social and language studies), while the remaining participants all studied math-related subjects (e.g., mathematics, economics, or engineering).

All students were tested in the context of a larger project evaluating amongst others the effects of attention-deficit/hyperactivity disorder (ADHD) on number processing. However, since the focus of the present study was on healthy individuals, we did not consider the data of participants that were either diagnosed with ADHD (7 participants) or displayed symptoms consistent with ADHD according to the Adult ADHD Self-Report Scale-V1.1 (ASRS-V1.1) (30 participants). In addition to this, one participant had to be excluded due to a diagnosis of dyslexia. This reduced our initial sample to 90 students, of which none reported to have any learning difficulties and/or neuropsychological disorders.

For those 90 participants, outliers were identified for each of the measures included in the present study. A total of 9 participants had to be removed from the population sample, since their performances fell 2.5 standard deviations (*SD*) below or above the mean group performances on at least one of the measures. All analyses were thus conducted on 81 healthy university students.

7.3.2 Procedure and tasks

Participants were tested individually during two 90 min testing sessions. Sessions were run on separate days to prevent any possible effects of fatigue. The time difference between the two testing sessions was not fixed, so that students could sign up for the sessions according to their preferences (e.g., during their free-time on campus between two lectures). The upper limit of one week between testing sessions was implemented to avoid too much variability in the range of time differences between sessions across participants.

Since the present study was conducted in the context of a larger project, a whole battery of different tests and questionnaires was implemented during the two testing sessions. However, to be as streamlined as possible, only those experiments required to answer the current research questions will be described in this section. Considering that a fixed order is standard practice and advisable in individual differences research (Carlson & Moses, 2001), all participants performed the tests in the same sequence. On the first testing day, participants completed the Object-Spatial Imagery Questionnaire (OSIQ; Blajenkova, Kozhevnikov, & Motes, 2006), the parity judgment task (Dehaene et al., 1993), the mental rotations test (MRT-A; Peters et al., 1995), and the magnitude classification task (van Galen & Reitsma, 2008).The second testing day comprised the untimed battery of arithmetic operations (Rubinsten & Henik, 2005; Shalev et al., 2001). Computerized tasks were programmed in E-prime (Version 1.2 or 2.0.8.79) and administered using a Dell Laptop with a 15.6 in. color monitor (1024 x 768 pixels).

7.3.2.1 Parity judgment and magnitude classification tasks

The design of the ***parity judgment task*** was adapted from Dehaene et al. (1993) and allowed us to determine number-space associations in a task with ***implicit numerical magnitude processing***. The experiment consisted of 144 experimental trials divided equally across two blocks. Each experimental trial started with an empty black-bordered square on a white background (sides 100 pixels, border 2 pixels). After 300 ms, one of eight possible stimuli (Arabic digits 1, 2, 3, 4, 6, 7, 8 or 9), presented in black on a white background in font Arial point size 64, appeared in the center of the black-bordered square and remained for 1300 ms. The inter-trial interval consisted of a blank screen of 1300 ms. Participants had to judge as quickly as possible whether the centrally presented single Arabic digit was odd or even by pressing either the ‘‘A’’ or ‘‘L’’ key on a standard QWERTZ keyboard. In the first block, all participants had to press the “A”/”L” key for odd/even digits respectively. This stimulus-response mapping was reversed for all participants in the second block. Each target digit was displayed exactly nine times per block. The sequence in which the target stimuli appeared was identical for all participants. However, it was pseudo-randomized in a way that no target digit could appear twice in a row, and the correct response could not be on the same side more than three times consecutively. Each block started with 12-20 training trials, depending on response accuracy. If accuracy was at least 70%, participants could directly proceed to the experimental trials after 12 training trials. Participants were given a small break half-way through each block.

The design of the ***magnitude classification task*** was adapted from the literature (e.g., Bull, Marschark, & Blatto-Valle, 2005; Ito & Hatta, 2004; van Galen & Reitsma, 2008) and allowed us to determine number-space associations in a task with ***explicit numerical magnitude processing***. The experiment was identical to the parity judgment task with the exception that participants had to judge whether the centrally presented single Arabic digit was smaller or larger than five by pressing either the ‘‘A’’ or ‘‘L’’ key. In the first block, all participants had to press the “A”/”L” key for smaller/larger digits respectively. This stimulus-response mapping was reversed for all participants in the second block.

Data analysis and reliability

Data from the training sessions was not analyzed. The mean error rate on experimental trials was 2.83% and 2% in the parity judgment and magnitude classification tasks respectively ($F(1, 80) = 13.95$, $p < .001$, $\eta p2 = .15$). Errors were not further analyzed. Reaction times (RTs) shorter or longer than 2.5 *SD* from the individual mean were considered as outliers and discarded prior to data analysis (3.02% and 3.1% of all correct trials in the parity judgment and magnitude classification tasks respectively, $F(1, 80) = .27$, $p = .61$, $\eta p2 = .003$).

SNARC regression slopes were computed using the individual regression equations method suggested by Fias, Brysbaert, Geypens, and D’ Ydewalle (1996). First, RTs were averaged separately for each digit and each response side for every participant. Individual RT differences (dRTs) were then calculated by subtracting for each digit the mean left-sided RT from the mean right-sided RT. The resulting dRTs were subsequently submitted to a regression analysis, using digit magnitude as predictor variable. Unstandardized ***SNARC regression slopes*** were taken as a measure of the ***strength of SNAs in terms of the inclination of the regression lines***. Negative regression weights reflected SNAs in the expected direction (faster left-/right-sided RTs for small/large digits respectively) with more negative regression slopes corresponding to stronger number-space associations.

In addition to the regression analysis, we also calculated correlations between dRTs and magnitude yielding individual SNARC effect sizes. To have normally distributed scores, Pearson’s r values were Fisher z-transformed. These ***SNARC effect sizes*** were taken as a measure of the ***strength of SNAs in terms of the fit of dRTs to the regression lines*** (Pinhas, Tzelgov, & Ganor-Stern, 2012; Tzelgov, Zohar-Shai, & Nuerk, 2013). Effect sizes closer to the absolute value of 1 corresponded to stronger number-space associations.

An important point worth considering here is that calculating dRTs for individual digits does not prevent a possible bias of parity status on lateralized RTs. This so-called MARC effect (reflecting faster left-/right-sided RTs for odd/even digits respectively, see Nuerk et al., 2004) might negatively affect the overall fit of dRTs to the regression line, especially in the parity judgment task[3]. As such, we collapsed RTs to an even and an odd digit separately for each response side and each participant and computed dRTs for each of the four resulting magnitude categories (i.e., very small [1, 2], small [3, 4], large [6, 7], and very large [8, 9], Pinhas et al., 2012; Tzelgov et al., 2013; see also Hoffmann, Pigat et al., 2014). This was done for both parity judgment and magnitude classification tasks to allow for better comparisons between the parity and magnitude SNARC effect sizes. The classical approach using individual digits was nonetheless used to calculate SNARC regression slopes to permit direct comparison with the results reported in previous SNARC effect studies.

To further analyze the pattern of dRTs and to test hypotheses regarding the shape of SNAs in the parity judgment and magnitude classification tasks (i.e., continuous versus categorical shapes respectively), we performed stepwise multiple linear regression analyses on either the parity or magnitude dRTs including both linear and categorical magnitude predictors.

To assess reliability, we calculated split-half reliabilities for the unstandardized parity and magnitude SNARC regression slopes using the odd–even method to control for systematic influences of practice or tiring within the tasks. Trials were odd–even half-split (based on order of appearance) and two SNARC regression slopes were calculated separately for each participant in each task. The correlation coefficients were Spearman–Brown corrected to get a reliability estimate for the entire set of items. Spearman-Brown corrected correlation coefficients were r = .55 and r = .78 in the parity judgment and magnitude classification task

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[3] In the present study, a tendency for a main effect of parity status on dRTs was revealed for the parity judgment (F = 3.61, p = .06, ηp2 = .04, odd dRT = 10.46 ms, even dRT = -19.9 ms), but not the magnitude classification task (F = .01, p = .92, ηp2 = .0, odd dRT = -5.85 ms, even dRT = -6.28 ms), indicating the presence of a MARC effect in the former but not the latter task.

respectively. According to Pearson and Filon's z for comparison of two non-overlapping correlations based on dependent samples, uncorrected bivariate correlation coefficients differed significantly between the two tasks (parity judgment: r = .38 versus magnitude classification: r = .64, z = -2.3, p = .02). Reliability was thus significantly lower in the parity judgment than the magnitude classification task.

To determine whether low reliabilities (especially in the parity judgment task) might be due to the influence of outliers, we performed linear regression analyses between odd and even SNARC regression slopes and subsequently identified influential data points based on the conventional Cook's distances criterion of > 4/N (see Viarouge, Hubbard, & McCandliss, 2014). Analysis revealed three influential data points with Cook's distances greater than .0494 (i.e., 4/81*)* for the parity judgment task. After removal of these participants, the correlation between odd and even parity SNARC regression slopes improved from r = .38 to r = .51, yielding a Spearman-Brown corrected reliability estimate of r = .68, comparable to r = .698 reported in the study of Cipora and Nuerk (2013). The correlation between odd and even magnitude SNARC regression slopes also improved after exclusion of six Cook's distances outliers from r = .64 to r = .7, yielding a Spearman-Brown corrected reliability estimate of r = .82. Without the inclusion of the aforementioned respective influential data points (i.e., N = 3 for parity judgments and N = 6 for magnitude classifications), uncorrected bivariate correlation coefficients no longer differed significantly between implicit and explicit tasks according to Fisher's z for comparison of two correlations based on independent groups (z = -1.85, p > .05).

Split-half reliabilities were also calculated for the parity and magnitude SNARC effect sizes. Spearman-Brown corrected correlation coefficients were r = .35 and r = .73 in the parity judgment and magnitude classification task respectively and were significantly different (Pearson and Filon's z = -2.76, p < .01). Reliability was thus again significantly lower in the parity judgment task. Considering the very low reliability estimate for the parity SNARC effect sizes in the present study and in general the negative impact of unreliable measurement on correlation and regression analyses outcomes (e.g., the underestimation of relations and as such the increased risk of type II errors), we decided not to consider SNARC effect sizes in the present correlation and regression analyses. Results for the parity and magnitude SNARC effect sizes are nonetheless reported in the supplementary material.

7.3.2.2 Untimed battery of arithmetic operations

We administered the untimed battery of arithmetic operations (Rubinsten & Henik, 2005; Shalev et al., 2001) to determine ***arithmetic performance***. This battery consists of 20 number facts, 32 complex arithmetic problems, 8 decimal problems and 20 fractions.

Data analysis and reliability

As in Hoffmann, Mussolin et al. (2014), we scored 1 point for every correctly solved arithmetic problem and expressed accuracies as percentages (i.e., ArithACC). Cronbach's alpha for the entire test (i.e., all 80 items) was .72 and thus sufficiently high (e.g., Nunnally, 1978).

7.3.2.3 Mental rotations test

We administered the 24-item mental rotations test (MRT-A; Peters et al., 1995) to measure ***spatial visualization ability***. For each item, participants were presented with a target figure and four comparison figures, which were 2-dimensional drawings of 3-dimensional geometric shapes composed of cubes. Two of the comparison figures were rotated versions of the target figure, while the remaining two comparison figures were mirror images. Participants were instructed to identify the two rotated versions of the target figure. They had four minutes to complete the first twelve items, a short break, and then four minutes to complete the remaining items.

Data analysis and reliability

Mental rotation skills were given by the number of items where both of the two rotated versions of the target figure were correctly identified (i.e., maximum score = 24). The mental rotations test was internally consistent with a Cronbach's alpha of .87. This value is comparable to the ones reported in previous studies (e.g., Caissie, Vigneau, & Bors 2009; Geiser et al., 2006) and also higher than the average alpha of .83 reported in Psychology journals (Osborne, Christensen, & Gunter, 2001).

7.3.2.4 Object-Spatial Imagery Questionnaire

We used the Object-Spatial Imagery Questionnaire (OSIQ; Blajenkova, Kozhevnikov, & Motes, 2006) to determine ***visualization profile***. This 30-item questionnaire consists of 15 spatial scale items and 15 object scale items. The spatial scale provides a measure of an individual's aptitude and preference for processing schematic images and the spatial relations between objects. Conversely, the object scale is an estimate of an individual's aptitude and preference for imaging colorful, picture-like images. Participants were asked to rate each item on a 5-point scale with 1 labelled "totally disagree" and 5 labelled "totally agree".

Data analysis and reliability

For each participant, average object and spatial scale scores were calculated. To allow for comparison between the two visualization styles, z-scores were computed for each scale (Blazhenkova, Becker, & Kozhevnikov, 2011). The difference between individual z-scores (i.e., object z-score – spatial z-score) was then used as an index of the participants' visualization profile, with positive and negative differences indicating preferences for object and spatial visualization styles respectively. A difference of zero indicated a mixed visualization profile with no preferences for either spatial or object visualization styles. Cronbach's alpha for the object and spatial scale scores were .82 and .87 respectively, thus indicating a high level of internal consistency for each subscale. These values are in line with those reported by Blajenkova et al. (2006), and either above or close to the acceptable range according to McKelvie's guidelines for judging the psychometric properties of imagery questionnaires (McKelvie, 1994).

All descriptive information can be found in Table 1.

Table 1. Descriptive Information	
Variable	**All participants**
Gender (f/m)	40/41
Age (years)	23.38 (3.23)
Handedness (r/l)	77/4
Parity SNARC regression slope	-10.07 (12.82)
Parity SNARC effect size	-.72 (1.04)
Magnitude SNARC regression slope	-5.2 (13.1)
Magnitude SNARC effect size	-.4 (1.14)
ArithACC (%)	92.04 (5.42)
Mental rotation (score)	13.23 (5.35)
Visualization profile (z-score difference)	0 (1.31)

Note. Standard deviations are shown in parentheses.

7.3.3 Statistical analyses

First of all, we conducted *correlation analyses* to determine the relation between number-space associations in the parity judgment and magnitude classification tasks as well as their associations with arithmetic performance, spatial visualization ability, and visualization profile. Considering the non-perfect reliabilities of the variables included in this study (especially the parity SNARC regression slopes), we corrected bivariate correlations for attenuation using Spearman's correction for attenuation formula.

We then performed two separate *multiple linear regression analyses* on either the parity or magnitude SNARC regression slopes. It is important to note here that we were not interested in the overall fit of any of the two regression models. Goodness of fit and its level of significance are only important in focused models, where one intends to explain as much variance as possible in the dependent variable with all of the predictors included in the model (i.e., model-oriented approach, for a discussion see Hagquist & Stenbeck, 1998). The present approach was, however, factor-oriented in that we were interested in the effects of individual predictors when controlling for the influences of possible confounders. More concretely, we aimed to determine whether the numerical and/or spatial variable(s) that were significantly correlated with number-space associations in the parity judgment and/or magnitude classification tasks (based on the present outcomes) could also explain a significant amount of variance in these respective SNAs when controlling for the effects of the remaining cognitive factors included in the regression models (not necessarily predicting the SNA outcome variable). We were also interested in whether there was a difference in the predictive validity of these variables depending on the implicit or explicit nature of the task. SNARC regression slopes were also included as predictor in each of the regression models to determine whether magnitude SNAs could significantly predict parity SNAs (and vice-versa) when partialling out the effects of the numerical and spatial factors commonly associated with either or both of these number-space associations. As such, we will interpret the effects of individual predictors regardless of the overall fit of the two regression models.

Finally, *simple and multiple additive moderation analyses* were performed using Hayes' PROCESS macro for SPSS to investigate whether the relation between the parity and magnitude SNAs was conditional upon any of the cognitive variables included in this study. In the present case, the parity and magnitude SNAs functioned as outcome and predictor variable respectively. Moderation is thus depicted by the significant effect of the product term between the magnitude SNA and the moderator on the parity SNA, while controlling for the effects of the two factors included in the product term. A bootstrapping approach with 10.000 bootstrap samples was used for each analysis. Significance was determined at 95% bias-corrected confidence intervals. To avoid multicollinearity issues, all variables were mean centered prior to analyses. Only unstandardized regression coefficients were reported. The Johnson-Neyman computational technique was used to identify the values of the moderator for which the parity and magnitude SNAs showed a significant association. This technique identifies the value(s) within the measurement range of the moderator, where the conditional effect of the magnitude SNA transitions between not statistically significant to statistically significant. Considering that categorizing continuous data via median-splits can be associated with some disadvantages such as the loss of information and statistical power and the population-dependency of a participant's group membership (e.g., Cohen, 1983; Cohen & Cohen, 1983; Irwin & McClelland, 2003; Maxwell & Delaney, 1993), conducting moderation analyses and by this means keeping the continuous nature of the variables is more appropriate in the present case than using factorial analysis of variance with categorized data and looking for interaction effects.

7.4 Results

7.4.1 SNARC descriptives

The mean *SNARC regression slopes* were significantly negative in both tasks (parity SNARC regression slope = -10.07, *SD* = 12.82, $t(80) = -7.07$, $p < .001$, magnitude SNARC regression slope = -5.2, *SD* = 13.1, $t(80) = -3.57$, $p = .001$). A repeated-measures ANOVA on the SNARC regression slopes revealed a main effect of task ($F(1, 80) = 7.14$, $p < .01$, $\eta p2 = .08$), thus indicating stronger SNAs in the parity judgment than the magnitude classification task in terms of the inclination of the regression lines.

A main effect of task was also observed for the *SNARC effect sizes* ($F(1, 80) = 3.97$, $p = .05$, $\eta p2 = .05$), with larger absolute values for mean SNARC effect sizes in the parity judgment (Fisher transformed z-score = -.72, *SD* = 1.04) than the magnitude classification task (Fisher-transformed z-score = -.4, *SD* = 1.14). This highlights again stronger SNAs in implicit than explicit tasks in terms of the fit of dRTs to the regression lines.

Significant correlations were observed between SNARC regression slopes and effect sizes for both the parity judgment ($r = .74$, $p < .001$) and magnitude classification tasks ($r = .81$, $p < .001$), indicating a relation between steeper regression slopes and better fits of dRTs to the regression lines in both tasks. However, as already mentioned before, we will focus on SNARC regression slopes rather than SNARC effect sizes for all subsequent correlation and regression analyses. This is done not only because the former measure is more commonly reported in SNARC studies (Wood et al., 2008), but also because of the very low reliability of the parity SNARC effect sizes, potentially increasing the risk of type II errors in the following correlation and regression analyses. All analyses including SNARC effect sizes are, however, reported in the supplementary material.

Considering the shape of SNAs, only the continuous predictor accounted for variance in the parity dRTs when considering dRTs computed for individual digits (R^2 = .7, $F(1, 6)$ = 14.04, b = -10.07, $t(1, 6)$ = -3.75, p = .01), while changes in the magnitude dRTs were solely explained by the categorical predictor (R^2 = .92, $F(1, 6)$ = 69.35, b = -29.18, $t(1, 6)$ = -8.33, $p < .001$). These results thus confirm assumptions about continuously and categorically distributed SNAs in the parity judgment and magnitude classification task respectively. Conversely, when considering dRTs computed for the four magnitude categories, their variance was best explained by the continuous magnitude predictor in both implicit (R^2 = .93, $F(1, 2)$ = 25.4, b = -17.43, $t(1, 2)$ = -5.04, p = .04) and explicit (R^2 = .96, $F(1, 2)$ = 49.06, b = -9.23, $t(1, 2)$ = -7.0, p = .02) tasks.

7.4.2 Correlation analyses

The correlation between the parity and magnitude SNARC regression slopes trended towards significance (r = .2, p = .07). Parity SNARC regression slopes also significantly correlated with arithmetic performance, with steeper slopes (i.e., stronger SNAs) corresponding to weaker arithmetic skills (r = .22, p = .05). No such relation was evidenced for the magnitude SNARC regression slopes (r = .12, p = .3). A positive trend was, however, observed between the latter and visualization profile (r = .2, p = .07), indicating stronger SNAs in the magnitude classification task in participants with a spatial visualization profile (i.e., with a more negative z-score difference). Finally, SNARC regression slopes did not correlate with spatial visualization ability, which co-varied with arithmetic performance and visualization profile. Attenuated and disattenuated correlation coefficients are shown in the upper and lower part of Table 2 respectively.

Table 2. Correlation Analysis					
	1.	**2.**	**3.**	**4.**	**5.**
1. Parity SNARC regression slope	-	**.20#**	**.22***	**-.06**	**-.02**
2. Magnitude SNARC regression slope	.31	-	**.12**	**-.03**	**.20#**
3. Arithmetic performance	.35	.16	-	**.25***	**-.25***
4. Spatial visualization ability	-.09	-.04	.32	-	**-.28***
5. Visualization profile	-.03	.23	-.29	-.30	-

Note. Attenuated correlation coefficients are displayed in bold in the upper part of the table. Disattenuated correlation coefficients are displayed in the lower part of the table. **p* < .05 (non-significant when adjusting for multiple comparisons using Holm-Bonferroni), #*p* = .07.

7.4.3 Multiple linear regression analyses

None of the two regression models reached significance as an overall model (parity SNARC regression slopes as DV: R^2 = .09, $F(4, 76) = 1.89$, $p = .12$, magnitude SNARC regression slopes as DV: R^2 = .1, $F(4, 76) = 2.06$, $p = .09$), indicating that the different numerical and spatial regressors in combination did not explain a significant amount of variance in either implicit or explicit SNARC regression slopes. However, considering that we were interested in the effects of individual predictors when controlling for the influences of possible confounders and consequently the present approach was factor- rather than model-oriented, we will continue by interpreting the significant effects of individual predictors.

In accordance with the correlation analyses outcomes, arithmetic performance and visualization profile either significantly predicted or trended towards being significant predictors of SNARC regression slopes in the parity judgment ($b = 0.52$, $t(76) = 1.87$, $p = .07$) and magnitude classification tasks ($b = 2.38$, $t(76) = 2.06$, $p = .04$) respectively (see Tables 3 and 4). On the other hand, despite the trend observed in the correlation analyses, the magnitude SNARC regression slopes were not a significant predictor of the parity SNARC regression slopes and vice-versa (b = 0.18, $t(76)$ = 1.57, p = .12) after controlling for arithmetic performance, spatial visualization ability, and visualization profile.

Regression analyses thus suggest that SNAs in implicit and explicit tasks rely on different cognitive mechanisms. However, considering the non-perfect reliabilities of some of the variables included in the regression models (notably the parity SNARC regression slopes), the absence of a significant relation between the different SNAs might result from the low reliability of the parity SNARC regression slopes. In multiple regression analysis, low reliabilities can lead to erroneous findings in that the risk of type II errors is increased for the predictors with poor reliability. Underestimation of the predictive validity of the variables with low reliability could then cause the overestimation of the effects of confounders in the regression models, thereby potentially manifesting in type I errors for those variables (Osborne & Waters, 2002). We thus need to be careful before making claims about the independence of underlying cognitive processes based on the regression outcomes. Altogether, considering low reliabilities, no definite conclusions about the mechanisms underlying SNAs in implicit and explicit tasks can be drawn from the present correlation and regression analyses.

Table 3. Multiple Linear Regression Analysis on the Parity SNARC Regression Slopes

Model	*b*	*SE-b*	ß	*t*	*p*
Constant	-53.15	25.12		-2.12	.04
Magnitude SNARC regression slope	0.18	0.11	0.18	1.57	.12
Arithmetic performance	0.52	0.28	0.22	1.87	.07
Spatial visualization ability	-0.27	0.28	-0.11	-0.98	.33
Visualization profile	-0.33	1.16	-0.03	-0.29	.78

Note. R^2 = .09, adj. R^2 = .04, $F(4, 76)$ = 1.89, p = .12.

Table 4. Multiple Linear Regression Analysis on the Magnitude SNARC Regression Slopes					
Model	***b***	***SE-b***	**ß**	***t***	***p***
Constant	-33.53	26.02		-1.29	.2
Parity SNARC regression slope	0.18	0.12	0.18	1.57	.12
Arithmetic performance	0.32	0.29	0.13	1.13	.26
Spatial visualization ability	0.04	0.29	0.02	0.15	.89
Visualization profile	2.38	1.15	0.24	2.06	.04

Note. R^2 = .1, adj. R^2 = .05, $F(4, 76)$ = 2.06, p = .09.

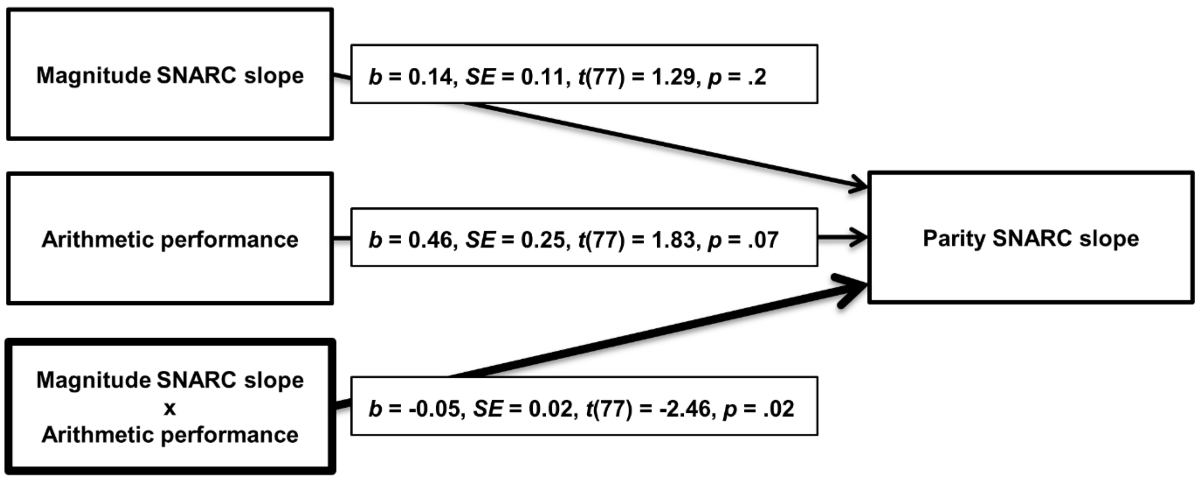
7.4.4 Simple and multiple additive moderation analyses

Considering that the correlation and multiple linear regression analyses failed to provide unequivocal evidence for a relation between number-space associations in the parity judgment and magnitude classification tasks, we tested whether the relationship between the two SNARC regression slopes could potentially be moderated by the cognitive factors also related to their respective strengths (i.e., arithmetic performance and visualization profile).

We therefore calculated interaction terms between the magnitude SNARC regression slopes and arithmetic performance as well as visualization profile. We then evaluated in separate models whether any of these interaction terms significantly predicted the parity SNARC regression slopes, while controlling for the variables included in the respective product terms.

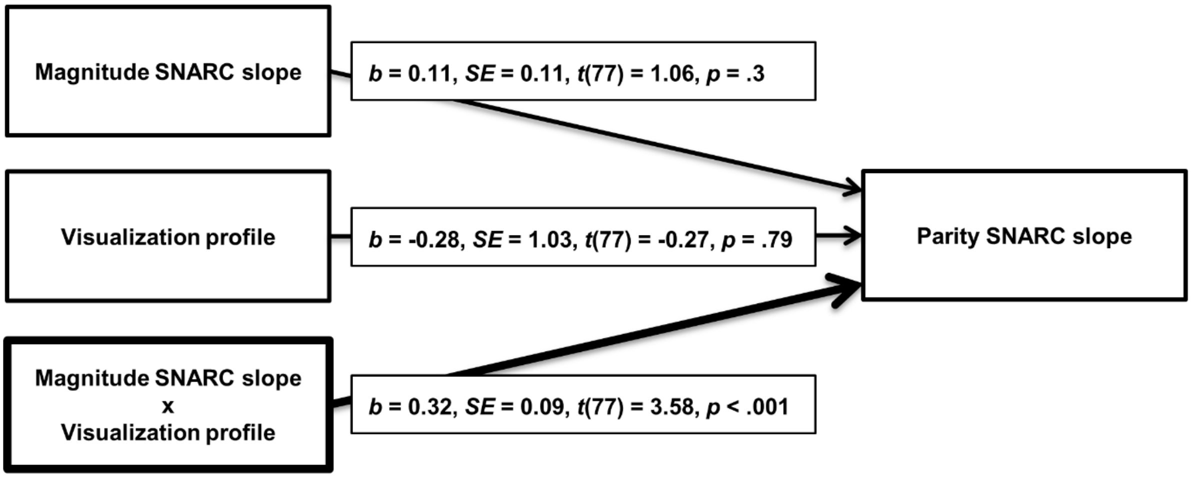
The *first simple moderation analysis* revealed that the interaction between the magnitude SNARC regression slopes and *arithmetic performance* accounted for a significant proportion of the variance in the parity SNARC regression slopes (ΔR^2 = .07, b = -0.05, $t(77)$ = -2.46, p = .02, Figure 1), when controlling for the effects of the magnitude SNARC regression slopes and arithmetic performance. This supports the fact that the level of arithmetic performance significantly moderated the relationship between SNAs in the parity judgment and magnitude classification tasks. When examining the conditional effect at different values of the moderator using the Johnson–Neyman technique, a significant positive relation between number-space associations in the two tasks was observed in individuals with lower arithmetic performance. Conversely, the parity and magnitude SNARC regression slopes were unrelated in the remaining participants. The value of ArithACC specifying the region of significance for the positive relation between the two SNAs was -1.57, corresponding to the uncentered ArithACC score of 90.47%. Roughly a third of the participants featured arithmetic performances below this critical value.

Figure 1. Simple Moderation Analysis Results for Arithmetic Performance with Unstandardized Regression Coefficients



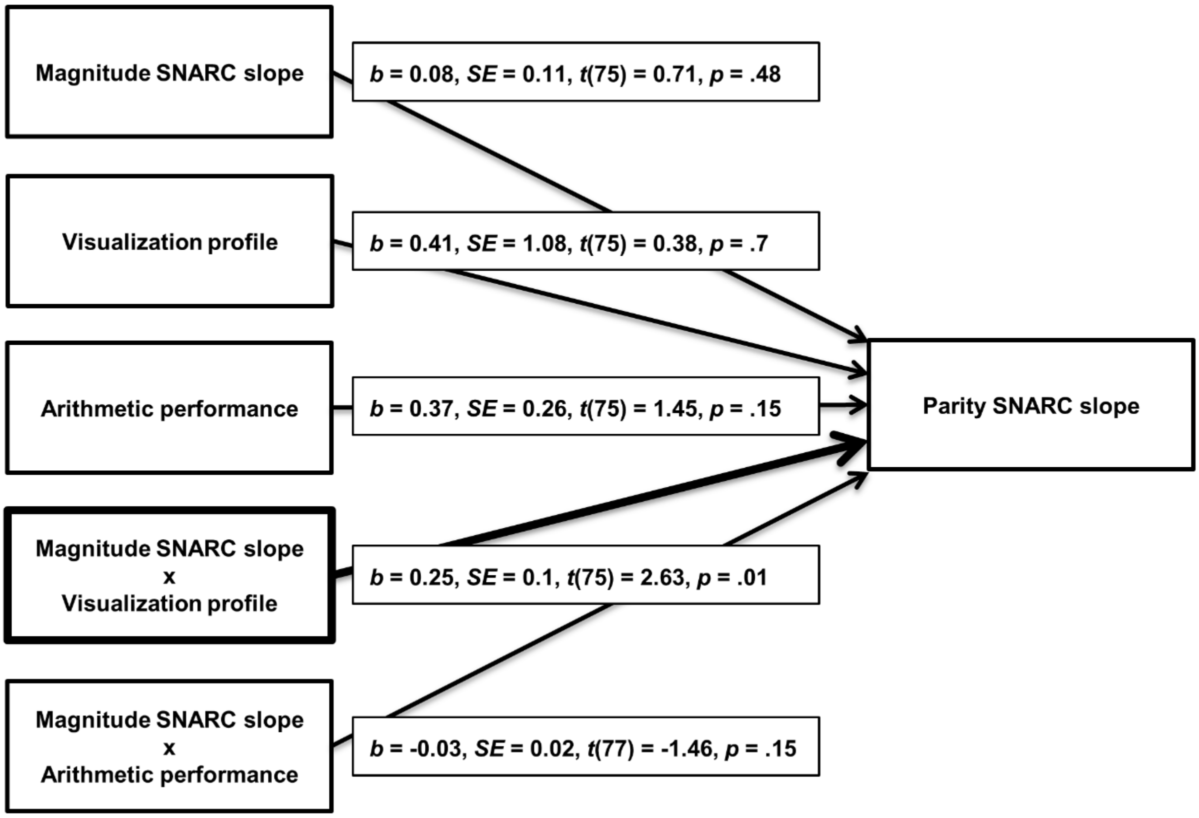
The *second simple moderation analysis* indicated that the interaction between the magnitude SNARC regression slopes and *visualization profile* was also a significant predictor of the parity SNARC regression slopes (ΔR^2 = .14, *b* = 0.32, *t*(77) = 3.58, *p* < .001, Figure 2), when controlling for the effects of the magnitude SNARC regression slopes and visualization profile. Visualization profile thus also significantly moderated the relationship between SNAs in the parity judgment and magnitude classification tasks. Considering the Johnson-Neyman technique, a significant positive relation between the parity and magnitude SNARC regression slopes was observed in individuals featuring more positive z-score differences (i.e., in individuals with object visualization profiles). The z-score difference specifying the region of significance for this positive relation was 0.29. 43% of the population featured z-score differences above this critical value. Interestingly, in individuals displaying z-score differences below -1.57, a significantly negative relationship was revealed between the two SNAs. This finding thus indicated that in individuals with spatial visualization profiles, stronger magnitude SNAs were associated with less pronounced parity SNAs. However, only 12% of the participants displayed z-score differences below this critical negative value. No relation between the different number-space associations was observed in the remaining 45% of individuals, featuring z-score differences between -1.57 and 0.29 (i.e., in individuals with less pronounced spatial visualization profiles and almost completely mixed visualization profiles).

Figure 2. Simple Moderation Analysis Results for Visualization Profile with Unstandardized Regression Coefficients



Considering the moderating effects of arithmetic performance and visualization profile when tested in separate models, a *multiple additive moderation analysis* was finally conducted to investigate whether the relationship between number-space associations in the parity judgment and magnitude classification tasks was simultaneously and to an equal extent moderated by both of these variables. Results indicated that in conjunction the two variables significantly moderated the aforementioned relationship, since simultaneously adding the two product terms (i.e., magnitude SNARC regression slopes x arithmetic performance and magnitude SNARC regression slopes x visualization profile) to the linear regression model yielded a significant increase in R^2 (ΔR^2 = .14, $F(2, 75) = 6.78$, $p = .002$) compared to when these terms were absent from the model. In other words, the simultaneous inclusion of the two product terms significantly increased (notably by 14%) the proportion of the variability in the parity SNARC regression slopes that was initially predicted by the model without the addition of these terms. However, the critical question is whether each of these two variables can moderate the relationship between the parity and magnitude SNAs over and above the moderating effect of the other. Interestingly, adding the magnitude SNARC regression slopes x visualization profile interaction term to the regression model, which already included the product term between arithmetic performance and the magnitude SNARC regression slopes, triggered a significant 7% increase in the amount of variance explained in the parity SNARC regression slopes (ΔR^2 = .07, *b* = 0.25, *t*(75) = 2.63, *p* = .01, Figure 3).Visualization profile thus moderated the relationship between number-space associations in the parity judgment and magnitude classification tasks even after controlling for the moderating effect of arithmetic performance. Conversely, the addition of the magnitude SNARC regression slopes x arithmetic performance product term to the regression equation, which already included the interaction term between the magnitude SNARC regression slopes and visualization profile, only caused a non-significant 2% increase in the model's capacity to predict variability in the parity SNAs (ΔR^2 = .02, *b* = -0.03, *t*(75) = -1.46, *p* = .15, Figure 3). Arithmetic performance did thus no longer moderate the relationship between the different number-space associations, when controlling for the moderating effect of visualization profile. When considering the influence of the magnitude SNARC regression slopes on the parity SNARC regression slopes at the means and at +/- 1 *SD* from the means of the two moderators (i.e., ArithACC and z-score differences, see Figure 4 for an illustration), a significantly positive relation between the two SNAs was observed in individuals with an object visualization profile especially when they also displayed average (*b* = 0.41, *t*(75) = 2.69, *p* = .01) or below average arithmetic performance (*b* = 0.57, *t*(75) = 3.81, *p* < .001). Conversely, a negative associations was revealed in participants with spatial visualization profiles and above average arithmetic performances (*b* = -0.42, *t*(75) = -2.17, *p* = .03). No relationship between the parity and magnitude SNARC regression slopes could be observed in individuals with a mixed visualization profile at any level of arithmetic performance.

Figure 3. Multiple Additive Moderation Analysis Results with Unstandardized Regression Coefficients



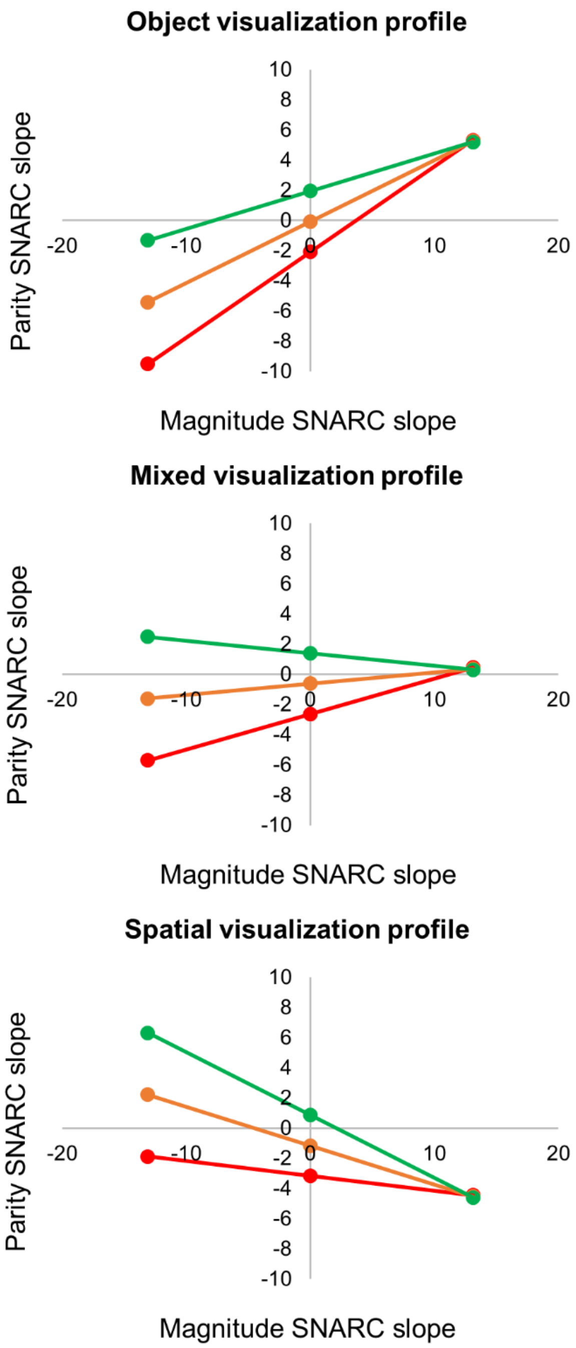


Figure 4. The effects of the magnitude on the parity SNARC regression slopes at the means and at -/+ one SD of arithmetic performances (i.e., low, average, high) and visualization profile (i.e., spatial, mixed, object).

7.5 Discussion

The present study aimed to determine whether number-space associations in tasks with implicit and explicit magnitude processing result from a single predominant spatial account or from multiple task-dependent spatial coding mechanisms. We adopted an individual differences approach to study the relation between the parity and magnitude SNARC effects and the extent of their associations with arithmetic performance, spatial visualization ability and visualization profile at the population level. Additionally, we performed moderation analyses to determine whether the relation between number-space associations in implicit and explicit tasks depended on individual differences in the aforementioned cognitive factors.

7.5.1 Arithmetic performance and visualization profile determine the relation between number-space associations in implicit and explicit tasks

A tendency for a positive correlation between the parity and magnitude SNARC regression slopes was observed at the population level. This outcome is in line with the recent findings of Cheung et al. (2015), highlighting a positive association between SNAs in implicit and explicit tasks. These findings thus suggest that spatial-numerical interactions in tasks with implicit and explicit magnitude processing tend to arise from at least partially overlapping (shared) spatial coding mechanisms. This is clearly in accordance with previous studies, providing evidence for the predominance of a single (verbal) spatial coding account regardless of the nature of the task (e.g., Gevers et al., 2010).

Conversely, SNAs in the parity judgment and magnitude classification tasks were related to different cognitive variables, namely arithmetic performance and visualization profile respectively. Moreover, regression analyses indicated that number-space associations in the magnitude classification task did not significantly predict spatial-numerical interactions in the parity judgment task (and vice-versa) when controlling for the effects of arithmetic performance, spatial visualization ability, and visualization profile. Altogether, these results thus suggest that number-space associations in tasks with implicit and explicit magnitude processing underlie at least partially unrelated spatial coding mechanisms. These findings are in line with the principle component analysis of van Dijck and colleagues (2012), indicating that SNAs in the parity judgment and magnitude classification tasks were placed in two separate components. The present results also agree with studies on hemi-neglect patients, reporting atypical SNARC effects only in tasks involving explicit magnitude processing (Priftis et al., 2006; Zorzi et al., 2012). Finally, finding evidence for task-dependent spatial coding mechanisms fits nicely with the context dependency of number-space associations reported by Georges et al. (2015), where the spatial nature of the cognitive processes accounting for number-space associations depended on task instructions.

Although interesting per se, the results of the correlation and regression analyses were relatively inconclusive and provided somehow conflicting results. Their outcomes did thus not allow us to fully resolve inconsistencies in the literature concerning the cognitive origins of number-space associations. One explanation for these inconsistent results might be the non-perfect reliabilities of some of the variables included in this study, especially the parity SNARC regression slopes. Considering that low reliability generally leads to the underestimation of the true relation between two factors (and as such the increased risk of type II errors), the absence of a relation between the parity and magnitude SNARC effects especially in the regression analyses might simply result from the low reliability of the parity SNARC regression slopes. As such, we need to be careful before making claims about the independence of underlying cognitive mechanisms solely based on the aforementioned analyses. Altogether, considering low reliabilities, no firm conclusions about whether SNAs in implicit and explicit tasks result from similar or unrelated spatial coding mechanisms can be drawn from the present correlation and regression analyses.

In a final step, we therefore performed moderation analyses to determine whether the relation between number-space associations in implicit and explicit magnitude processing tasks and as such the relatedness of their underlying spatial coding mechanisms might be conditional upon individual differences in the cognitive factors also explaining individual variations in the strengths of the SNAs (namely arithmetic performance and visualization profile). Interestingly, the relation between the two SNARC effects was indeed moderated by visualization profile and arithmetic performance. This outcome thus allowed us to shed a completely new light onto the reasons why some studies provide evidence for the predominance of a single account (e.g., Gevers et al., 2010), while others claim that the spatial coding mechanisms underlying number-space associations depend on the implicit or explicit nature of the task (e.g., van Dijck et al., 2009). Number-space associations in tasks with implicit and explicit magnitude processing were positively related in individuals with an object visualization profile (i.e., preferences for the object visualization style) especially if they featured average or below average arithmetic performance. Conversely, a negative relation between the two SNAs was observed in participants with a spatial visualization profile and above average arithmetic performance. These observations thus suggest that both kinds of visualizers rely on a single predominant spatial coding account regardless of the task. However, the nature of the cognitive mechanisms giving rise to number-space associations seems to vary depending on the type of visualizer, considering significantly positive and negative associations between the two SNAs in object- and spatial-visualizers respectively. The activation of different spatial coding mechanisms depending on an individual's visualization preferences is not surprising, considering that previous observations indicated the adoption of procedural and conceptual strategies when solving numerical tasks in object- and spatial-visualizers respectively (Chrysostomou et al., 2013). Moreover, individuals with different visualization style preferences were shown to employ different strategies in creative mathematical tests (Pitta-Pantazi, Sophocleous, & Christou, 2013). While spatial-visualizers clearly opted for analytic strategies, this was not the case for object-visualizers. In contrast to object and spatial imagers, no association between the parity and magnitude SNARC regression slopes could be observed in individuals with a mixed visualization profile (i.e., individuals without a specific preference for a particular visualization style), suggesting that these individuals activate different spatial coding processes depending on the implicit or explicit nature of the task. One possible explanation for the absence of a significant relation in these participants is that they flexibly switch between the different spatial coding strategies depending on the task requirements, considering their lack of preference for a particular visualization style. Overall, these findings suggests that individual differences in visualization profile and arithmetic performance determine whether number-space associations in implicit and explicit magnitude processing tasks co-vary and supposedly rely on similar or unrelated spatial coding mechanisms. This might then provide an explanation for the previous inconsistencies in the literature regarding the cognitive mechanisms underlying SNAs.

7.5.2 Arithmetic performance and visualization profile differentially affect number-space associations in implicit and explicit tasks

By investigating to what extent number-space associations in implicit and explicit magnitude processing tasks can be explained by individual differences in arithmetic performance, spatial visualization ability, and visualization profile, we not only attempted to shed further light onto the relatedness of the spatial coding mechanisms underlying the different SNAs, but also aimed to advance our understanding of the cognitive processes primarily contributing to each of the SNARC effects at the population level.

Considering number-space associations in the ***parity judgment task***, the present results confirmed the previously reported association between stronger parity SNAs (in terms of steeper SNARC regression slopes) and weaker arithmetic performance (Hoffmann et al., 2014, but see Cipora & Nuerk, 2013), at least when considering the correlation analyses outcomes. We did, however, not find any evidence for an effect of visualization profile. This implies that number-space associations in tasks with implicit reference to numerical magnitude (or at least in tasks involving parity judgments) might not rely (or to a lesser extent) on visuospatial processing resources in the right parietal cortex and/or on object processing areas in the lateral occipital complex, shown to be associated with spatial visualization (Lamm, Bauer, Vitouch, & Gstättner, 1999) and object visualization (Motes, Malach, & Kozhevnikov, 2008) respectively. Parity SNAs might rather arise from categorical verbal-spatial coding mechanisms not involving these areas (Jager & Postma, 2003). This assumption is in accordance with the studies of Gevers et al. (2010) and van Dijck et al. (2009), indicating the predominance of verbal-spatial coding of numerical information in the parity judgment task. Nonetheless, as already addressed before, any relations between the parity SNARC regression slopes and the other cognitive variables included in the present study need to be interpreted with caution, given the low reliability of the parity SNARC effect.

The absence of a significant relation between number-space associations in the parity judgment task and visualization profile might for instance also result from the low reliability of the parity SNARC regression slopes. The involvement of visuospatial processing resources in the emergence of parity SNAs should thus not be completely ruled out based on the present observations.

In contrast to the parity SNAs, number-space associations in the ***magnitude classification task*** were significantly predicted only by visualization profile, thereby adding this variable to the list of cognitive factors accounting for the high individual variability of number-space associations. Following the aforementioned line of thought, magnitude SNAs might thus underlie the activation of right parietal and/or lateral occipital areas related to visualization abilities (Lamm et al., 1999, Motes et al., 2009). Especially the activation of parietal regions might play a role in the emergence of number-space associations in the magnitude classification task, considering that greater preferences for the spatial visualization style (i.e., greater reliance on parietal pathways) were associated with stronger magnitude SNAs. In other terms, the activation of parietal regions seems to be essential for spatial-numerical interactions in the magnitude classification task, as individuals with preferences for the object visualization style, depending to a lesser extent on these areas, featured less pronounced magnitude SNARC effects. The present findings thus suggest that number-space associations in explicit magnitude processing tasks arise from visuospatial coding of numerical magnitudes along the MNL thought to have its locus in the parietal cortex (Dehaene, Piazza, Pinel, & Cohen, 2003). Relying on a left-to-right oriented MNL seems intuitive in tasks involving explicit magnitude processing especially if numerical magnitudes need to be compared to a certain referent (e.g., 5), since categorizing digits visuospatially as left (smaller than 5 to the left on the MNL) and right (larger than 5 to the right on the MNL) might be helpful for successful task completion. It would thus be interesting to see whether stronger magnitude SNAs are associated with better performance (e.g., fewer errors) on this task. However, considering that overall error rates are generally quite low for magnitude classifications, one might want to increase task difficulty by imposing time constraints or by displaying the numerical stimuli only very briefly.

On the other hand, no relation was observed between magnitude SNAs and arithmetic performance. One possible explanation for this is that number-space associations in the magnitude classification task do not depend (or to a lesser extent) on executive control, which might mediate the relationship between the parity SNARC effect and arithmetic performance (see Cipora et al., 2015 for the effects of mediating variables). Less involvement of executive control during magnitude classifications might well be the case, if one assumes that activation rather than inhibition of the magnitude-associated spatial code is helpful for successful task completion. Conversely, parity SNAs were previously shown to depend on inhibitory control, in that stronger number-space associations in the parity judgment task were associated with weaker inhibitory control (Hoffmann, Pigat et al., 2014). Moreover, the effect of inhibitory control on arithmetic performance is well-documented (e.g., Gilmore, Keeble, Richardson, & Cragg, 2015).

Another point worth addressing here is that number-space associations were never affected by spatial visualization ability (i.e., mental rotation skills) regardless of the task. This observation is in accordance with the study of Viarouge et al. (2014), who also failed to find evidence for a relation between parity SNAs and 3D mental rotation skills. Similarly, Gibson and Maurer (2016) did not observe a relation between the magnitude SNARC effect and performances in a standardized test of visuospatial skills (DTVP-2) in children. Nevertheless, it might be slightly surprising when considering the aforementioned association between number-space associations in the magnitude classification task and the participants' visualization profiles, which were shown to relate to visualization abilities (Blajenkova et al., 2006; Blazhenkova et al., 2011; see also present results). One possible explanation is that although visualization style and corresponding ability depend on common processing resources (Kozhevnikov, Blazhenkova, & Becker, 2010), style and ability still represent partially independent cognitive constructs. Evidence in favor of this distinction is provided by

Kozhevnikov, Chen and Blazhenkova (2013). They showed that although object and spatial visualization styles and abilities both related to artistic and scientific creativities respectively, visualization style could still reliably predict creativity even after removing the shared variance between style and ability. Visualization style thus requires the use of some unique processing mechanisms beyond ability, which seem to be important for creativity and also affect the magnitude SNAs in the present case. Another explanation for the aforementioned discrepancy is that visualization profile, as it is defined in the present study, reflects the preference for one particular visualization style over the other. On the other hand, the mental rotation task only provided information about the participants' spatial visualization ability, without taking into account their object visualization ability. Since it was the contrast between the two visualization styles that related to the strength of number-space associations in the magnitude classification task, it might also be the contrast between the two visualization abilities that critically predicts SNAs, even though spatial visualization ability in itself was not related to spatial-numerical interactions.

7.5.3 Limitations and future studies

An important point worth mentioning here is that moderation analysis assumes a causal relationship in that its application requires a causal theory and design behind the data (e.g., Wu & Zumbo, 2008). Even though there is no evidence for a causal relationship between the different SNAs, it is more likely that number-space associations in the magnitude classification task determine spatial-numerical interactions in the parity judgment task than the reverse, given that the latter only emerges latter in development. While parity SNAs only seem to appear around 3rd grade (Berch, Foley, Hill, & Ryan, 1999), a tendency for magnitude SNAs can already be evidenced as early as Kindergarten (Hoffmann, Hornung, Martin, & Schiltz, 2013). Moreover, children as young as 4-years-old were shown to display a SNARC-like effect in a non-symbolic number classification task (Patro & Haman, 2012). Considering these findings and the fact that parity SNAs have been more commonly studied with regard to cognitive factors explaining individual differences in number-space associations (e.g., Hoffmann, Pigat et al., 2014; Shaki, Fischer, & Petrusic, 2009; Viarouge et al., 2014), we decided to use it as our dependent variable.

Moreover, we need to bear in mind the non-perfect reliabilities of some of the variables included in this study, especially the parity SNARC regression slopes. Low reliabilities might be explained by the small number of repetitions per digit for each response side in the present study (i.e., 9 repetitions), since a much higher split-half reliability of r = .698 was reported for the parity SNARC regression slopes when using 20 repetitions per digit (Cipora & Nuerk, 2013; see also Cipora & Wood, 2012; Cipora et al., 2016). The length of the scale can however not account for the significant difference in reliabilities between the parity judgment and magnitude classification tasks, since both tasks were equally long. Nevertheless, significantly more errors were committed in the parity judgment than the magnitude classification task, such that more items had to be removed from the analyses in the former. This might thus at least to some extent explain the significant difference in reliabilities between the implicit and explicit number processing tasks in the present study. Moreover, since participants committed significantly more errors when indicating the parity status of digits, guessing might have been more likely in the parity judgment task. Considering that chance success due to guessing can contribute to error variance and as such negatively affect the reliability of binary classification tasks, this might provide another explanation for the significantly lower reliability in the parity judgment task.

Regardless of the underlying reasons, low reliability in correlation and regression analyses generally leads to the underestimation of the true relation between two factors (and as such the increased risk of type II errors). Underestimation of the predictive validity of the variables with low reliability could then cause the overestimation of the effects of confounders in regression models, thereby potentially manifesting in type I errors for those variables (Osborne & Waters, 2002). Poor reliability of the parity SNARC regression slopes might thus underlie the lack of significant relation between implicit and explicit SNAs especially in our regression analyses. We thus need to be careful before making claims about the (in-)

dependence of underlying cognitive processes. Poor reliability might also provide an alternative explanation for the lack of association between the parity SNAs and visualization profile. The involvement of visuospatial processing resources in the emergence of parity SNAs should thus not be completely ruled out based on the present observations. Altogether, considering low reliabilities, the present correlation and regression analyses did not allow us to draw any firm conclusions about whether SNAs in implicit and explicit tasks arise from similar or unrelated spatial coding mechanisms. Fortunately, moderation analyses enabled us to shed further light onto the mechanisms underlying number-space associations in the different tasks. In order to avoid low reliabilities of SNAs in future individual differences studies, it appears advisable to increase stimuli repetitions from 9 to 20, as it was suggested by Cipora and Wood (2012) and also successfully implemented by Cipora and Nuerk (2013; see also Cipora et al., 2016).

On another note, the present study only determined how individual differences in numerical and spatial factors predicted variability in the parity and magnitude SNAs in the entire study population (i.e., comprising all types of individuals). An interesting idea for future research might thus be to investigate how arithmetic performance, spatial visualization ability and visualization profile relate to number-space associations in implicit and explicit magnitude processing tasks in either object-, spatial-, or mixed-visualizers. This should shed further light onto the spatial nature of the cognitive mechanisms contributing to spatial-numerical interactions in each of the different kinds of visualizers. One might for instance assume that number-space associations in both implicit and explicit magnitude processing tasks are predicted by the same cognitive variable in individuals where SNAs co-varied. However, considering that number-space associations co-varied positively and negatively in object- and spatial-visualizers respectively, the main cognitive predictor of the two SNAs should differ between the former and latter individuals.

Moreover, despite the fact that the present study provided evidence for the activation of visuospatial coding mechanisms in tasks with explicit magnitude processing, no assumptions can be made about the additional contribution of the WM account, since our analyses focused on the effects of numerical and spatial factors rather than executive control. To evaluate the WM account, one could for instance investigate how individual differences in (verbal and/or visuospatial) WM predict number-space associations in implicit and explicit magnitude processing tasks. This question could be addressed at the population level as well as in the different types of visualizers. Moreover, individual differences in (verbal and/or visuospatial) WM might be another factor moderating the relation between number-space associations in the parity judgment and magnitude classification tasks.

In addition to this, considering the effect of visualization profile on lower-level numerical processes, such as number-space associations during explicit magnitude judgments, one might wonder whether this cognitive factor also influences non-symbolic number comparisons or plays a role in the emergence of mathematical difficulties (e.g., dyscalculia). Furthermore, the effect of the verbal cognitive style might be examined especially with regard to the parity judgment task, given that parity SNAs are commonly assumed to arise from verbal-spatial coding mechanisms (e.g., Gevers et al., 2010) and also seemed to depend less on visuospatial processes in the present study.

Finally, since the spatial nature of the coding mechanisms underlying number-space associations was shown to depend on task instruction (Georges et al., 2015), it might be interesting to determine whether visualization profile and/or arithmetic performance also moderate the context-dependency of number-space associations in this case. Considering that the predominance of verbal-spatial coding mechanisms was evidenced under verbal instructions, while both verbal- and visuospatial coding mechanisms were activated under spatial instructions, it might be likely that only some individuals switched to the visuospatial account under physical instructions, while others activated verbal-spatial processes regardless of the task instructions.

7.5.4 Conclusion

The present findings show that individual differences in visualization profile and arithmetic performance determined whether number-space associations in implicit and explicit magnitude processing tasks co-varied and supposedly relied on similar or unrelated spatial coding mechanisms. Significantly positive and negative association between the parity and magnitude SNAs were observed in object-visualizers with lower arithmetic performances and spatial-visualizers with higher arithmetic performances respectively. These findings thus suggest the predominance of a single spatial coding account in both types of visualizers. The spatial nature of the account, however, differs between object- and spatial-visualizers. No association between the parity and magnitude SNAs was revealed in mixed-visualizers, suggesting the activation of task-dependent spatial coding processes. Moreover, arithmetic performance and visualization profile differentially related to the parity and magnitude SNAs respectively. We can thus conclude (with the interpretational cautions imposed by the low reliability of the parity SNARC regression slopes) that visuospatial coding mechanisms seem to contribute to number-space associations in the magnitude, but not (or to a lesser extent) the parity judgment task (at least at the population level). .

Overall, this study helps explain some of the inconsistencies in the literature regarding the cognitive processes contributing to spatial-numerical interactions. It also highlights the usefulness of moderation analyses for unravelling how the relation between different numerical concepts varies between individuals, thereby potentially clarifying further inconsistencies in the numerical cognition literature.

7.6 References

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7.7 Supplementary Material

7.7.1 Supplementary results

7.7.1.1 Correlation analyses

The correlation between the parity and magnitude SNARC effect sizes was not significant ($r = .11$, $p = .31$). The parity SNARC effect sizes were also not correlated with arithmetic performance ($r = .11$, $p = .33$). Whether this null effect is due to the very low reliability of the parity SNARC effect sizes or indicates that arithmetic performance differentially relates to the parity SNARC regression slopes and effect sizes is not clear. A significant relation was, however, observed between the magnitude SNARC effect sizes and visualization profile ($r = .31$, $p < .01$), which is in accordance with the SNARC regression slope analyses. Attenuated and disattenuated correlation coefficients are displayed in the upper and lower part of the Supplementary Table 1 respectively.

Supplementary Table 1. Correlation Analysis

	1.	2.	3.	4.	5.
1. Parity SNARC effect size	-	**.11**	**.11**	**-.14**	**.21**
2. Magnitude SNARC effect size	.22	-	**.02**	**-.04**	**.31****
3. Arithmetic performance	.22	.03	-		
4. Spatial visualization ability	-.25	-.05		-	
5. Visualization profile	.36	.36			-

Note. Attenuated correlation coefficients are displayed in bold in the upper part of the table. Disattenuated correlation coefficients are displayed in the lower part of the table. **$p < .01$.

7.7.1.2 Multiple linear regression analyses

None of the two regression models computed with the SNARC effect sizes reached significance as an overall model (parity SNARC effect sizes as DV: $R^2 = .09$, $F(4, 76) = 1.77$, $p = .14$, magnitude SNARC effect sizes as DV: $R^2 = .11$, $F(4, 76) = 2.3$, $p = .07$).

Moreover, the parity SNARC effect sizes were not significantly predicted by any of the numerical or spatial factors included in the regression model. Conversely, the magnitude SNARC effect sizes were significantly affected by visualization profile even after controlling for the other cognitive variables included in the model (b = 0.29, $t(76)$ = 2.83, $p < .01$). The latter finding is in line with the regression analysis on magnitude SNARC regression slopes.

Supplementary Table 2. Multiple Linear Regression Analysis on the Parity SNARC Effect Sizes

Model	*b*	*SE-b*	ß	*t*	*p*
Constant	-3.74	2.03		-1.85	.07
Magnitude SNARC effect size	0.04	0.11	0.04	0.35	.73
Arithmetic performance	0.04	0.02	0.19	1.64	.11
Spatial visualization ability	-0.03	0.02	-0.13	-1.10	.28
Visualization profile	0.16	0.10	0.20	1.66	.10

Note. R^2 = .09, adj. R^2 = .04, $F(4, 76)$ = 1.77, p = .14.

Supplementary Table 3. Multiple Linear Regression Analysis on the Magnitude SNARC Effect Sizes

Model	*b*	*SE-b*	ß	*t*	*p*
Constant	-2.26	2.21		-1.02	.31
Parity SNARC effect size	0.04	0.12	0.04	0.35	.73
Arithmetic performance	0.02	0.02	0.09	0.80	.43
Spatial visualization ability	0.01	0.03	0.04	0.31	.76
Visualization profile	0.29	0.10	0.33	2.83	<.01

Note. R^2 = .11, adj. R^2 = .06, $F(4, 76)$ = 2.3, p = .07.

7.7.1.3 Simple moderation analyses

The *first simple moderation analysis* revealed that the interaction between the magnitude SNARC effect sizes and *arithmetic performance* did not account for a significant proportion of the variance in the parity SNARC effect sizes (ΔR^2 = .01, b = -0.02, $t(77)$ = -1.07, p = .29), when controlling for the effects of the magnitude SNARC effect sizes and arithmetic performance. In contrast to the SNARC regression slope analyses, the relation between the strengths of the parity and magnitude SNAs in terms of the fit of dRTs to the regression lines was thus not affected by the level of arithmetic performance.

On the other hand, the *second simple moderation analysis* indicated that the interaction between the magnitude SNARC effect sizes and *visualization profile* was a significant predictor of the parity SNARC effect sizes ($\Delta R^2 = .1$, $b = 0.22$, $t(77) = 2.95$, $p < .01$), when controlling for the effects of the magnitude SNARC effect sizes and visualization profile. Visualization profile thus significantly moderated the relation between the parity and magnitude SNARC effect sizes, which is in line with the SNARC regression slope analyses. Considering the Johnson-Neyman technique, a significantly positive relation was observed in individuals featuring more positive z-score differences (i.e., in individuals with object visualization profiles). The z-score difference specifying the region of significance for this positive relation was 1.13. 19% of the population featured z-score differences above this critical value. Interestingly, in individuals displaying z-score differences below -1.33, a significantly negative relation was revealed between the two SNARC effect sizes. 17% of the participants displayed z-score differences below this negative value. No relation between the different SNARC effect sizes was observed in the remaining 64% of individuals, featuring z-score differences between -1.32 and 1.12.

8 Study 4

Task Instructions Determine the Visuospatial and Verbal-spatial Nature of Number-Space Associations

Georges, C., Schiltz, C., & Hoffmann, D. (2015)

Georges, C., Schiltz, C., & Hoffmann, D. (2015). Task instructions determine the visuospatial and verbal–spatial nature of number–space associations. *The Quarterly Journal of Experimental Psychology, 68*(9), 1895-1909. doi: 10.1080/17470218.2014.997764

8.1 Abstract

Evidence for number-space associations comes from the spatial-numerical association of response codes (SNARC) effect, consisting in faster reaction times to small/large digits with the left/right hand respectively. Two different proposals are commonly discussed concerning the cognitive origin of the SNARC effect: the visuospatial account and the verbal-spatial account. Recent studies have provided evidence for the relative dominance of verbal-spatial over visuospatial coding mechanisms, when both mechanisms were directly contrasted in a magnitude comparison task. However, in these studies, participants were potentially biased towards verbal-spatial number processing by task instructions based on verbal-spatial labels. To overcome this confound and to investigate whether verbal-spatial coding mechanisms are predominantly activated irrespective of task instructions, we completed the previously used paradigm by adding a spatial instruction condition. In line with earlier findings, we could confirm the predominance of verbal-spatial number coding under verbal task instructions. However, in the spatial instruction condition, both verbal-spatial and visuospatial mechanisms were activated to an equal extent. Hence, these findings clearly indicate that the cognitive origin of number-space associations does not always predominantly rely on verbal-spatial processing mechanisms, but that the spatial code associated with numbers is context-dependent.

Keywords: Number-space associations; SNARC effect; cognitive origin; visuospatial; verbal-spatial.

8.2 Introduction

The SNARC effect is one important behavioural marker for the tight relationship between numerical and spatial representations (Dehaene, Bossini, & Giraux, 1993; for reviews, see de Hevia, Vallar, & Girelli, 2008; Wood, Willmes, Nuerk, & Fischer, 2008). It is based on the observation that individuals are typically faster on their left/right hand-side for relatively small/large numbers respectively when doing a binary classification judgment on single

Arabic digits. The cognitive origin of the SNARC effect, however, remains elusive. Two different proposals are most commonly discussed concerning the nature of the spatial information that is associated with numbers: the *visuospatial account* and the *verbal-spatial account* (i.e., Wood et al., 2008).

The dominant and most traditional *visuospatial* account is based on the idea that numbers are mentally represented along a continuous left-to-right-oriented representational medium (the mental number line; MNL) with small/large numbers located on the left/right side of the continuum respectively (Dehaene et al., 1993; Moyer & Landauer, 1967; Restle, 1970). Compelling evidence for the existence of such a MNL comes from the hemi-neglect literature (for a review, see Umiltà, Priftis, & Zorzi, 2009). Hemi-neglect patients with a (right) parietal lesion typically fail to orient their attention to the contralesional (left) hemispace (for a review, see Halligan, Fink, Marchall, & Vallar, 2003). This deficit in visuospatial attention becomes obvious when patients are required to indicate the midpoint of a physical line. They commonly shift their subjective midpoint too far to the right of the actual midpoint as if they were neglecting the leftmost part of the line. Zorzi, Priftis, and Umiltà (2002) extended this finding of physical neglect to the numerical domain. When hemi-neglect patients were asked to state the midpoint of a verbally given number interval (e.g. 1-9), they exhibited a bias towards a relatively larger number (e.g., 7), similar to their rightward bias in the physical line bisection task. Further evidence in favour of the MNL comes from the observation that digits can act as directional cues, inducing lateralized shifts in visuospatial attention depending on their magnitudes (e.g., Fischer, Castel, Dodd, & Pratt, 2003; Goffaux et al., 2012). Some findings let us however question the idea that the dimensional overlap between numerical and spatial representations is entirely of visuospatial nature. For instance, Priftis, Zorzi, Meneghello, Marenzi, and Umiltà (2006) reported a preserved SNARC effect in hemi-neglect patients, even though they exhibited a number interval bisection bias. Moreover, the MNL hypothesis cannot provide an explanation for the lack of correlation between the severity of hemi-spatial neglect and the size of the number interval bisection bias (van Dijck, Gevers, Lafosse, & Fias, 2012). On another note, a long-term association between numbers and space, as it is assumed by the MNL, can hardly justify the flexible nature of number-space associations. For example, the SNARC effect can be easily reversed by instructing participants to imagine numbers as being displayed on a clock face, possibly due to the fact that small and large numbers occur on the right and left side of the clock respectively (Bächtold, Baumüller, & Brugger, 1998). Additionally, Russian-Hebrew bilinguals displayed typical SNARC effects after reading a text in Russian, while their number-space associations were reversed after reading a Hebrew text (Shaki & Fischer, 2008). These findings thus question the idea of a stable long-term MNL representation.

An alternative view to the MNL hypothesis suggests that the SNARC effect arises from categorical *verbal-spatial* coding. As such, number-space interactions would result from an association between the verbal categorical concepts “small” and “left” as well as “large” and “right” (Gevers et al., 2010). In their polarity coding account, Proctor and Cho (2006) suggested that the stimulus and response alternatives in binary classification tasks are coded as negative and positive polarities. Accordingly, in the SNARC paradigm, a negative polarity would be assigned to small magnitudes and a positive polarity to large magnitudes on the stimulus dimension, while on the response dimension negative and positive polarities would be attributed to the left and right side respectively. The congruency between the polar codes on the stimulus and response dimensions would then give rise to the SNARC effect (see also the neural network model proposed by Gevers, Verguts, Reynvoet, Caessens, & Fias, 2006). Contrary to the visuospatial coding account (i.e., MNL hypothesis), the conceptual verbal-spatial coding account provides a potential explanation for the flexible nature of the SNARC effect, since the categorical concepts and/or polarity codes associated with the different numerical stimuli could easily vary depending on context. Another phenomenon supporting verbal-spatial numerical coding is the so-called linguistic markedness of response codes effect (MARC effect, Nuerk, Iversen, & Willmes, 2004), referring to an odd-left and even-right stimulus-response advantage. However, it remains unclear how the verbal-spatial account might explain phenomena such as the numerical distance effect (Moyer and Landauer, 1967) or the findings that number-space associations also occur in tasks without lateralized responses (e.g., Fischer et al., 2003).

Recently, Fias, van Dijck, and Gevers (2011) suggested a critical involvement of working memory (WM) processes to explain the flexible nature of number-space associations, considering the serial position of numbers in WM as a determinant factor. Accordingly, the SNARC effect would arise from the serial position of digits in WM (ordered according to their magnitudes), with positions from the beginning/end of the sequence eliciting faster left-/right-sided responses respectively. Evidence in favour of the WM account was provided by studies showing that the SNARC effect indeed critically depended on the availability of WM resources (Herrerra, Macizo, & Semenza, 2008; van Dijck, Gevers, & Fias, 2009).

In order to get a clearer picture of the nature of the mechanisms underlying number-space associations, Gevers et al. (2010) first tested whether the visuospatial and verbal-spatial coding mechanisms could by themselves and thus independently of the other explain the SNARC effect (Experiments 1 and 2). They found that both verbal-spatial and visuospatial coding mechanisms were sufficient to obtain number-space associations. In a second instance, they directly pitted the two possible coding mechanisms against each other to determine their relative strengths in explaining number-space associations (Experiments 3 and 4). To dissociate the confound of both coding mechanisms typically encountered in the classical SNARC paradigm (e.g., faster left-sided responses for small digits could result from an association either between the verbal concepts “small” and “left” or between small digits and the left side of physical space), they randomly varied the position of the verbal labels “Left” and “Right” to appear on the left or right physical response sides. They thereby created word congruent trials, where there was a correspondence between the verbal labels and their side of appearance, and word incongruent trials, where no correspondence occurred (i.e., the verbal labels “Left”/”Right” appeared on the right/left physical response side respectively). Participants were instructed to respond to the verbal labels regardless of their physical side of appearance (e.g., click on the verbal labels “left”/”right” for small/large numbers respectively). An interaction between number magnitude and physical response side regardless of the associated verbal label would predict the visuospatial account, while an association between number magnitude and the verbal response labels irrespective of their side of presentation would favour the verbal-spatial account. Interestingly, clear evidence was found for the predominance of verbal-spatial number coding both in parity judgment and number comparison tasks.

While Imbo, Brauwer, Fias, and Gevers (2012) could replicate these findings in 9- and 11-year-old children, another study found evidence for the activation of verbal-spatial and visuospatial processing mechanisms depending on whether number-space associations were measured in the horizontal or vertical dimension respectively (M. Li, personal communication, October 12, 2014). Moreover, van Dijck, Gevers, and Fias (2009) showed that visuospatial and verbal WM differentially contributed to the SNARC effect depending on the number processing task. These observations thus clearly indicate that the associations between numbers and space are not absolute, and that the nature of the spatial information associated with numbers might depend on contextual aspects.

The idea that number-space associations cannot be attributed to a single underlying processing mechanism, but that they result from the activation of multiple different spatial codes was nicely depicted in the study of van Dijck, Gevers, Lafosse, and Fias (2012). Using principle component analysis to unravel the relationships between number processing tasks typically used to illustrate the association between numbers and space, they found that a three component solution yielded the best fit of the data pattern. These findings thus clearly refute the predominance of a single coding mechanism, and suggest that number-space interactions more likely arise from the interplay between different coding mechanisms whose activational extent is task-dependent.

Given the context-dependency of the underlying processing mechanisms for number-space associations, the findings of Gevers et al. (2010) and Imbo et al. (2012) need to be interpreted with caution. Task instructions in both studies were of verbal nature, as participants were required to respond to the verbal labels but had to ignore their physical side of appearance. However, previous studies have stressed the importance of task instructions in experimental studies (Galfano, Rusconi, & Umilta, 2006; Ristic, Wright, & Kingstone, 2006; Shaki & Gevers, 2011). It is thus unclear whether instruction-mediated response strategies induced the relative dominance of verbal-spatial over visuospatial number coding or whether the verbal-spatial coding account is the dominant processing mechanism regardless of task instructions and thus independent of context.

To determine whether participants were biased towards verbal-spatial coding mechanisms in the studies of Gevers et al. (2010) and Imbo et al. (2012) and elucidate whether task instructions could be another determining factor in the choice of coding strategy, we completed their paradigm by adding a spatial instruction condition. Using the same task as in Gevers et al. (2010), Experiment 4, and Imbo et al. (2012), we not only instructed participants to respond to a certain verbal label irrespective of its physical side of appearance (verbal instruction condition), but we also required them to respond to either the left or right physical response side regardless of the displayed verbal labels (spatial instruction condition). Comparing the relative strength of the visuospatial and verbal-spatial coding mechanisms between the spatial and verbal instruction conditions enabled us to determine whether the cognitive origin of number-space associations is always predominantly of verbal nature or whether it varies with task instructions.

8.3 Methods

8.3.1 Participants

A total of 44 university students took part in this study. Participants were recruited from all kinds of study fields ranging from English literature and social sciences to mechanical engineering and computer science. Results from 41 participants were included in the data analysis – 20 were females, 2 were left-handed and their mean age was 21.6 years (*SD* = 2.95, range = 18-34 years). One participant was excluded due to premature abortion of the experiment and two because of a lack of adherence to the task instructions. Participants were either of Luxembourgish or German nationality and did not report to have any specific learning difficulties such as dyslexia or dyscalculia. They had normal or corrected to normal vision and were naive with respect to the objective of the study. All participants gave written informed consent and received 8€ for participation.

8.3.2 Apparatus and stimuli

The computerized task was programmed in E-prime (Version 2.0.8.79; Schneider, Eschman, & Zuccolotto, 2002) and administered using a Lenovo ThinkPad 61 Tablet Laptop with a 12.1 in. colour monitor (1024 × 768 Pixels), in a quiet room. Responses were given on a touch-sensitive screen with a pen using the participant's dominant hand.

Target stimuli were the Arabic digits 1 to 9 with the exception of 5. They were presented in black Courier New font (36-pt. type) in the centre of an empty black-bordered transparent square in the middle of a white screen background (sides 100 pixels, border 2 pixels).

8.3.3 Procedure

The experiment consisted of 648 trials in total, including 576 experimental trials, 32 catch trials and 40 practice trials.

Each experimental trial started with a black fixation cross (+; Courier New font, 18-pt. type) that was displayed for 750 ms in the centre of the screen. Subsequently, the German labels ''Links'' (English: "Left"; Courier New font, 14-pt. type) and ''Rechts'' (English: "Right") were presented on the left and right side of the screen. On half of the trials, the label ''Links'' appeared on the left side and the label ''Rechts'' on the right side (word congruent trials), while on the remaining half their positions were reversed (word incongruent trials). After 200 ms, one of the target stimuli appeared in the centre of the screen and remained until a response was given. In the verbal instruction condition, participants were instructed to touch the label “Links” for digits smaller than 5 and the label “Rechts” for digits larger than 5 - independent of their physical side of appearance (e.g., “touch the word “Links” for digits smaller than 5 regardless of whether it is displayed on the left or right side of the central digit”). In the spatial instruction condition, participants had to touch the left side of the screen for digits smaller than 5 and the right side of the screen for digits larger than 5 irrespective of the displayed label (e.g., “touch the word displayed on the left side of the screen for digits smaller than 5”). In both the verbal and spatial instruction conditions, stimulus-response mappings were reversed on half of the trials. The order of the stimulus-response mappings within each instruction condition as well as task instructions were counterbalanced across participants. Catch trials were only included in the spatial instruction condition to ensure that participants read and thus processed the labels before making a left- or right-sided response. Catch trials were identical to experimental trials with the exception that the German word “Zahl” (English: “Number”) was displayed on the left and right side of the central digit and that participants had to touch the central digit instead of making a left- or right-sided response. After each response made on experimental or catch trials, a black cross (x; Courier New font, 36-pt. type) appeared in the centre of an empty black-bordered transparent square in the middle of the white screen background. Participants needed to touch the cross to proceed to the next trial. This ensured that their hands had re-adopted a central position before making another left- or right-sided response. Target digits and the position of the labels varied randomly from trial to trial.

Each target digit was displayed 18 times on experimental trials in each mapping (i.e., 9 times on word congruent and incongruent trials) and appeared twice on catch trials in each mapping under spatial instructions. The two different mappings within each instruction condition were preceded by 10 practice trials to familiarize participants with the task (i.e., 10 practice trials per mapping under verbal instructions; 10 practice trials including 2 catch trials per mapping under spatial instructions). Participants were given a 10 s break halfway through each mapping. All participants completed both the verbal and spatial instruction conditions.

To ensure that participants were recruited from heterogeneous backgrounds (Hoffmann, Mussolin, Martin, & Schiltz, 2014; Wood et al., 2008), they completed a small questionnaire asking about their field of study, their interests in mathematics and any special association with numbers at the end of the experimental session.

8.3.4 Data analysis and interpretation

For the experimental trials, data analysis focused on median correct reaction times (RTs) and SNARC regression slopes. Errors were made on 2.29% and 1.4% of all the experimental trials in the verbal and spatial instruction conditions respectively, but were not further analysed.

For the catch trials, we only determined error rates, since they were merely included to ensure that participants read and thus processed the verbal labels in the spatial instruction condition. No errors were made on catch trials, thus indicating that participants had read the verbal labels even though they were completely irrelevant for successful task completion.

Considering previous findings on the gender-dependency of the SNARC effect (Bull, Cleland, & Mitchell, 2013), we first ran all our analysis including gender as a between-subject variable. Since we did not find any main effect of gender or any interactions with the within-subject variables (all *ps* > .05), we decided to drop this factor and excluded it from our further statistical analysis.

8.3.4.1 Median correct RTs

Median correct RTs were calculated based on the physical and verbal congruencies of the experimental trials (Figure 1).

Figure 1. Experimental conditions independent of task instructions. Correct responses are indicated in black. Conditions expected to yield shorter RTs when relying on visuospatial coding are outlined in blue; conditions expected to yield shorter RTs when relying on verbal-spatial coding are highlighted by orange shading.

Verbal Congruency		Physical Congruency	
		Congruent	Incongruent
	Congruent	L 2 R L 8 R	R 2 L R 8 L
	Incongruent	R 2 L R 8 L	L 2 R L 8 R

Physical congruency: refers to the congruency between the magnitude of the presented digit and the physical side of the participant's response. Trials were thus classified as physically congruent when participants had to respond on the left/right physical response side for small/large digits respectively regardless of the displayed verbal labels. Conversely, trials were considered as physically incongruent when the response had to be made on the right/left physical response side for small/large digits respectively. A main effect of physical congruency with faster RTs on physically congruent than incongruent trials irrespective of the verbal labels would provide evidence for visuospatial number coding.

Verbal congruency: refers to the congruency between the magnitude of the presented digit and the verbal label of the participant's response. Trials were thus categorized as verbally congruent when participants had to respond to the verbal labels "Left"/"Right" for small/large digits respectively regardless of their physical side of appearance. On the other hand, trials were classified as verbally incongruent when the response was given to the verbal labels "Right"/"Left" for small/large digits respectively. A main effect of verbal congruency with faster RTs on verbally congruent than incongruent trials regardless of their side of appearance would indicate verbal-spatial number coding.

8.3.4.2 Regression analysis

Two different types of SNARC effects were calculated for each instruction condition using regression analyses (Fias, Brysbaert, Geypens, & D' Ydewalle, 1996; Lorch & Myers, 1990) – the classical visuospatial SNARC effect and a verbal-spatial SNARC effect. The *visuospatial SNARC effect* was ascertained by separately calculating median correct RTs for each digit and each physical response side (left/right) irrespective of the displayed verbal labels for each participant and by subsequently computing RT differences between the right and left physical response sides for each digit (visuospatial dRTs). The *verbal-spatial SNARC effect* was determined by separately calculating median correct RTs for each digit and each verbal response label ("Left"/"Right") irrespective of their physical side of appearance for each participant and by then calculating RT differences between the "Right" and "Left" verbal response labels for each digit (verbal-spatial dRTs). Visuospatial and verbal-spatial dRTs were then entered into a regression analysis using digit magnitude as the predictor variable. Visuospatial and verbal-spatial regression weights (i.e., slopes) were used as an index of the size of the visuospatial and verbal-spatial SNARC effects respectively. Significantly negative visuospatial and verbal-spatial SNARC regression slopes would provide evidence for the corresponding visuospatial and verbal-spatial coding mechanisms.

In addition to this, we also compared visuospatial SNARC regression slopes in the word congruent and incongruent conditions (see Gevers et al., 2010; Imbo et al., 2012). A significantly negative visuospatial SNARC slope on both word congruent and incongruent trials would provide evidence for visuospatial number coding (i.e., participants are always faster on the left/right physical response side for small/large digits respectively regardless of the displayed verbal labels). Conversely, a visuospatial SNARC effect that is significantly negative on word congruent but significantly positive (i.e., reversed) on word incongruent trials would indicate verbal-spatial number coding (i.e., on word incongruent trials participants are faster on the right/left physical response sides for small/large digits respectively due to the right-/left-sided display of the verbal labels “Left”/”Right” respectively).

8.4 Results

8.4.1 Median correct RTs

Averages of the median correct RTs for the different instruction and congruency conditions are displayed in Table 1.

Median correct RTs were subjected to 2 x 2 x2 repeated measures ANOVA including instruction condition (verbal, spatial), physical congruency and verbal congruency as within-subject factors. We found a main effect of instruction condition ($F(1, 40) = 80.11$, $MSE = 40{,}360.82$, $p < .001$, $\eta_p^2 = .67$) as well as a main effect of physical ($F(1, 40) = 4.41$, $MSE = 12{,}097.35$, $p = .04$, $\eta_p^2 = .1$) and verbal ($F(1, 40) = 33.58$, $MSE = 9{,}376.56$, $p < .001$, $\eta_p^2 = .46$) congruency. Moreover, significant interactions were observed between instruction condition and physical congruency ($F(1, 40) = 5.53$, $MSE = 8{,}683.95$, $p = .02$, $\eta_p^2 = .12$), instruction condition and verbal congruency ($F(1, 40) = 18.91$, $MSE = 10{,}072.51$, $p < .001$, $\eta_p^2 = .32$) and between the two congruency measures ($F(1, 40) = 6.05$, $MSE = 2{,}917.31$, $p = .02$, $\eta_p^2 = .13$). The triple interaction between instruction condition, verbal congruency and physical congruency did not reach significance ($F(1, 40) = 0.84$, $MSE = 2{,}147.70$, $p = .36$, $\eta_p^2 = .02$).

Considering the aim of the present study, we focussed subsequent analyses on the significant interactions between instruction condition and physical congruency as well as instruction condition and verbal congruency.

The effect of physical congruency was only significant in the spatial instruction condition ($F(1, 40) = 5.35$, $MSE = 9{,}707.27$, $p = .03$, $\eta_p^2 = .12$), where participants were significantly faster on physically congruent than incongruent trials (physically congruent RT = 902.39 ms, physically incongruent RT = 952.72 ms). This thus suggests that visuospatial number coding was only activated under spatial instructions.

Conversely, the effect of verbal congruency was significant in the two instruction conditions (verbal instruction: $F(1, 40) = 28.17$, $MSE = 8{,}606.73$, $p < .001$, $\eta_p^2 = .41$; spatial instruction: $F(1, 40) = 17.31$, $MSE = 585.41$, $p < .001$, $\eta_p^2 = .3$). Under both instances, participants were significantly faster on verbally congruent than incongruent trials (verbal instruction: verbally congruent RT = 1073.09 ms, verbally incongruent RT = 1181.83 ms; spatial instruction: verbally congruent RT = 908.6 ms, verbally incongruent RT = 930.83 ms).

These results thus indicate that verbal-spatial number processing was activated in both the verbal (Gevers et al., 2010; Imbo et al., 2012) and spatial instruction conditions. Effect sizes however suggest that verbal-spatial coding was slightly weaker under spatial than verbal task instructions.

Table 1. Averages of median correct RTs for the different experimental trials in the verbal and spatial instruction conditions

Experimental Trials	Verbal Instruction	Spatial Instruction
All	1113.51 (158.34)	919.56 (131.82)
Physically Congruent	1109.79 (158.89)	902.39 (144.04)
Physically Incongruent	1117.88 (158.87)	952.72 (150.98)
Verbally Congruent	1073.09 (176.46)	908.6 (130.11)
Verbally Incongruent	1181.83 (173.27)	930.83 (135.65)

Note. Standard deviations are shown in parentheses; reaction times (RTs) are given in ms.

8.4.2 Regression analysis

Slopes were subjected to a 2 x 2 repeated measures ANOVA including instruction condition (verbal, spatial) and SNARC type (verbal-spatial, visuospatial) as within-subject variables. A significant interaction between instruction condition and SNARC type was observed ($F(1, 40) = 15.61$, $MSE = 1{,}052.85$, $p < .001$, $\eta_p^2 = .28$).

The effect of SNARC type was significant under verbal instructions (*F*(1, 40) = 19.45, *MSE* = 1,168.99, $p < .001$, $\eta_p^2 = .33$, see Figure 2A), indicating that visuospatial and verbal-spatial SNARC slopes were significantly different. Only the verbal-spatial SNARC slope was significantly negative (verbal-spatial slope = -36.34, *t*(1, 40) = -4.97, $p < .001$, Cohen's *d* = -1.57; visuospatial slope = -3.04, *t*(1, 40) = -1.27, $p = .21$), thus confirming the previously reported predominance of verbal-spatial number coding under verbal task instructions (Gevers et al., 2010; Imbo et al., 2012).

Conversely, we did not find a main effect of SNARC type under spatial instructions (*F*(1, 40) = 0.81, *MSE* = 1,146.6, $p = .37$, $\eta_p^2 = .02$, see Figure 2B). Both SNARC slopes were significantly negative (verbal-spatial slope = -8.6, *t*(1, 40) = -3.73, $p = .001$, Cohen's *d* = -1.18; visuospatial slope = -15.34, *t*(1, 40) = -2.1, $p = .042$, Cohen's *d* = -0.66), with no difference in their strengths (*t*(1, 40) = 0.9, $p = .37$). The size of the verbal-spatial SNARC effect was, however, significantly weaker in the spatial than the verbal instruction condition (-8.6 versus -36.34; *t*(40) = -3.65, $p = .001$, Cohen's *d* = -0.65).

These results thus confirm our analysis on median correct RTs, indicating a contribution of both coding mechanisms under spatial instructions with a relatively weaker influence of verbal-spatial number coding under spatial than verbal task instructions.

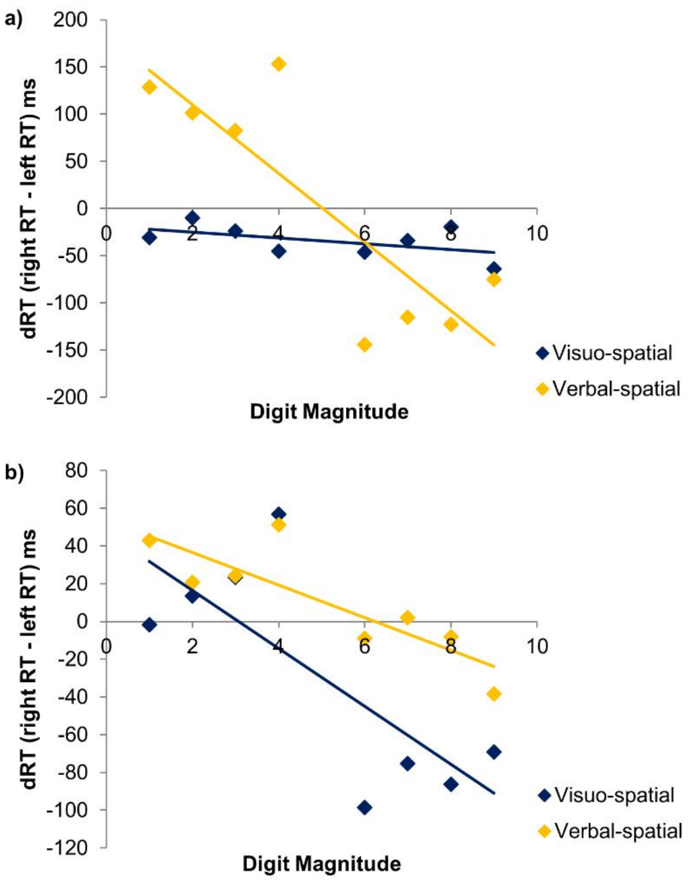

Figure 2. Reaction time difference (dRT) between the left and right physical response side as a function of digit magnitude (visuospatial regression slope in blue) and dRT between the verbal labels "Left" and "Right" as a function of digit magnitude (verbal-spatial regression slope in orange) in the verbal (A) and spatial (B) instruction condition.

To consolidate these observations and in accordance with the studies of Gevers et al. (2010) and Imbo et al. (2012), visuospatial SNARC slopes were also subjected to a 2 x 2 repeated measures ANOVA including instruction condition (verbal, spatial) and word congruency as within-subject variables. We observed a main effect of word congruency ($F(1, 40) = 27.98$, $MSE = 3{,}013.68$, $p < .001$, $\eta_p^2 = .41$) – SNARC slopes were significantly different on word congruent and incongruent trials. Most interestingly for the present study, the analysis revealed a significant interaction between instruction condition and word congruency ($F(1, 40) = 16.29$, $MSE = 2{,}676.08$, $p < .001$, $\eta_p^2 = .29$).

Under verbal instructions, the visuospatial SNARC slope was significantly negative on word congruent trials (slope = -40.14, $t(40) = -4.98$, p < .001, Cohen's $d = -1.57$), but reversed to positivity on word incongruent trials (slope = 37.81, $t(40) = 4.3$, $p < .001$, Cohen's $d = 1.36$, see Figure 3A).

Under spatial instructions, the visuospatial SNARC slope was also significantly negative on word congruent trials (slope = -21.98, $t(40) = -3.17$, $p = .003$, Cohen's $d = -1$, see Figure 3B). However, in the word incongruent condition, the SNARC slope did neither remain significantly negative nor reverse to positivity (slope = -9.23, $t(40) = -1.14$, $p = .26$, see Figure 3B).

These findings thus highlight again the predominance of verbal-spatial number coding only under verbal task instructions and the contribution of both coding mechanisms in the spatial instruction condition.

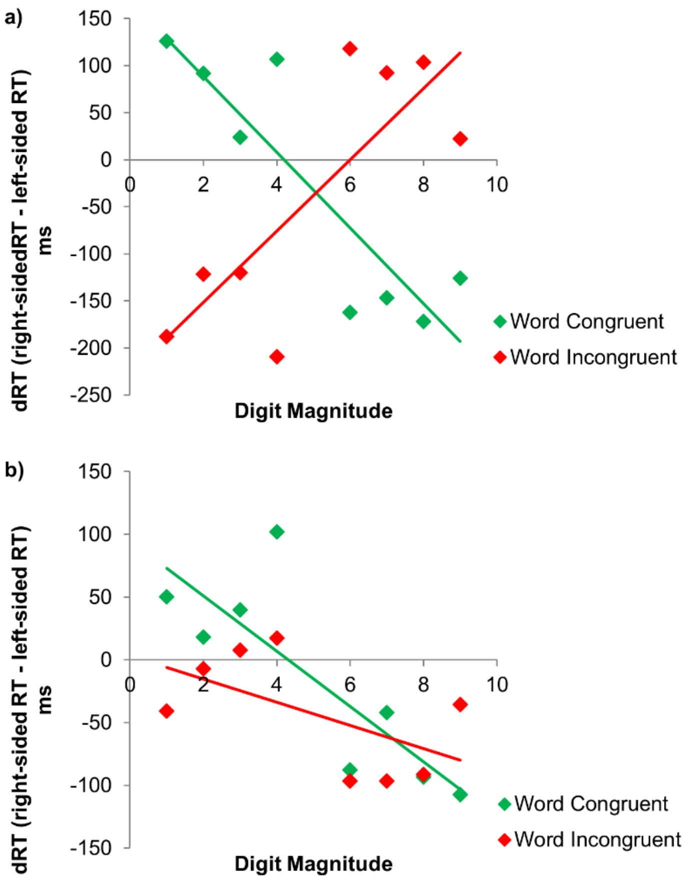

Figure 3. Reaction time difference (dRT) between the left and right physical response side as a function of digit magnitude on word congruent trials (regression slope in green) and word incongruent trials (regression slope in red) in the verbal (A) and spatial (B) instruction condition.

8.5 Discussion

To determine the cognitive origin of the SNARC effect, we investigated the respective influence of verbal-spatial and visuospatial coding strategies when pitted directly against each other. There has been recent evidence for the relative dominance of verbal-spatial over visuospatial coding mechanisms (Gevers et al., 2010; Imbo et al., 2012). However, in these studies, participants were potentially biased towards verbal-spatial number processing, since task instructions were based on verbal labels (i.e., instructions to respond to the verbal labels “Left” and “Right” regardless of their physical side of appearance). Moreover, considering recent evidence that numbers can be associated with different types of spatial information depending on the task at hand (M. Li, personal communication, October 12, 2014; van Dijck et al., 2009), we aimed to determine whether the verbal-spatial coding account is dominant irrespective of task instructions. To this end, we completed the original paradigm of Gevers et al. (2010) by adding a spatial instruction condition requiring participants to give left- and right-sided responses regardless of the displayed verbal labels.

In accordance with the previous findings of Gevers et al. (2010) and Imbo et al. (2012), we could confirm the predominance of verbal-spatial number coding under verbal task instructions. Interestingly, the verbal-spatial mechanism was also activated under spatial task instructions, suggesting that the spatial code associated with numbers is of verbal nature regardless of whether participants are put in a verbal or spatial context. This strong association between numbers and verbal concepts is not surprising given the crucial role of language in our society. Moreover, spatial language has been found to play a beneficial role even in non-linguistic spatial mapping tasks, highlighting its general importance for spatial cognition (Gentner, Özyürek, Gürcanli, & Goldin-Meadow, 2013).

Despite this tendency to associate numbers with verbal-spatial concepts, our data shows that verbal-spatial coding is not always the exclusive or predominant processing mechanism. When participants were placed in a visuospatial context by instructing them to associate digit magnitudes with physical space, visuospatial number coding was activated to an extent similar to that of verbal-spatial number coding.

Interestingly, our spatial instruction condition yielded a visuospatial magnitude SNARC effect that was slightly more negative (visuospatial SNARC slope = -15.34 ms, Figure 2B) than the one typically observed in the classical magnitude comparison task (Castronovo & Seron, 2007; Galen & Reitsma, 2008; van Dijck et al., 2009). One possible explanation for this observation might be that in the classical magnitude comparison task, we are unable to establish the relative contribution of verbal-spatial and visuospatial coding mechanisms to the resulting SNARC slope. Conversely, thanks to the addition of verbal-spatial labels, we know for certain that the classically computed (visuospatial) magnitude SNARC slope in the current experiment was entirely brought about by visuospatial number coding (in the case of verbal-spatial number coding, participants would have followed the verbal labels, resulting in a zero RT difference between left- and right-sided responses and thus in the absence of a visuospatial SNARC slope). This pure contribution of visuospatial coding strategies to the classical magnitude SNARC effect in the present study would then suggest that visuospatial coding tends to induce slightly stronger number-space associations than verbal-spatial number coding (at least under spatial instructions). This also fits nicely with the slightly less pronounced verbal-spatial compared to visuospatial SNARC effect under spatial instructions. Nonetheless, even though the visuospatial SNARC effect was slightly more negative than the verbal-spatial SNARC effect under spatial instructions, we need to bear in mind that this difference did not reach significance.

Another interesting point is that although the categorical shape of the visuospatial magnitude SNARC effect under spatial instructions (cf. Figure 2B) might seem surprising, given that numbers are not encoded as either “left” or “right” but have precise locations on a continuous MNL, it is clearly in accordance with previous studies (Bull, Marschark, & Blatto-Valle, 2005; Gevers et al., 2006; Nuerk, Bauer, Krummenacher, Heller, & Willmes, 2005; Shaki, Algom, & Petrusic, 2006). The categorical appearance of the magnitude SNARC effect (in contrast to the continuous parity SNARC effect) has previously been explained by the relatively slow processing of digit magnitudes that are close to the referent (i.e., 4 and 6) compared to digit magnitudes that are further away from the referent (i.e., 1 and 9, distance effect; Moyer & Landauer, 1967). Since the SNARC effect should be stronger when digit magnitude is processed more slowly and intensively, number-space associations for digits in the middle range of the numerical interval should be almost as strong as those for digits in the extremes of the numerical interval, thereby resulting in a categorical SNARC shape (Wood et al., 2008).

All in all, our findings show that number-space associations are not always exclusively of verbal nature, but that the spatial code associated with numbers is context-dependent – in a verbal context verbal-spatial coding mechanisms predominate, while both the verbal-spatial and visuospatial mechanisms are activated to an equal extent in a visuospatial context.

Our findings complement previous observations alluding to the context-dependency of the SNARC effect. For instance, M. Li (personal communication, October 12, 2014) showed that the extent to which the SNARC effect can be explained by visuospatial and verbal-spatial number coding is direction-dissociative. In other terms, it depends on whether number-space associations are measured in the horizontal (i.e., classical SNARC effect) or vertical dimension (i.e., vertical SNARC effect). In mainland Chinese participants, verbal-spatial number coding was the predominant processing mechanism using the horizontal magnitude SNARC task (task design was identical to Gevers et al., 2010, Experiment 4). Conversely, the visuospatial coding mechanism was predominantly activated in the vertical magnitude SNARC task, with small/large numbers being associated with the visuospatial top/bottom respectively, consistent with the top-to-bottom-oriented texts in Chinese.

In addition to this, van Dijck et al. (2009) showed that numbers can be associated with different spatial codes depending on the number processing task. While a verbal WM load was sufficient to prevent number-space interactions in the classical parity judgment but not the magnitude comparison task, holding visuospatial information in WM abolished the SNARC effect in the magnitude comparison but not the parity judgment task. This double-dissociation indicates that the magnitude SNARC effect predominantly relies on spatial codes of visuospatial nature, while number-space associations in the parity judgment task are primarily attributed to verbally-mediated spatial information. The predominant involvement of visuospatial and verbal-spatial cognitive processes in the magnitude and parity tasks respectively might not seem surprising, considering that in the magnitude comparison task target numbers can be easily categorized visuospatially as left (smaller than 5 to the left on the MNL) and right (larger than 5 to the right on the MNL), while labelling a number as “odd” or “even” in the parity judgment task seems more of a verbal exercise. Finding evidence for the involvement of verbally-mediated spatial processes in tasks based on verbal concepts, such as the parity judgment task, is thus in accordance with our data, highlighting the predominance of verbal-spatial number coding in a situation where individuals are explicitly instructed to associate digit magnitudes with verbal labels of spatial nature (i.e., “Left” and “Right”). On the other hand, considering the importance of visuospatial but not verbal WM for number-space associations in the classical magnitude comparison task, one might not have anticipated the activation of verbal-spatial number coding under spatial instructions. One explanation might be that the inclusion of the verbal labels “Left” and “Right” in our magnitude comparison paradigm was sufficient to prime verbally-mediated cognitive processes and thereby activate verbal-spatial number coding strategies also under spatial instructions, at least to an extent similar to that of visuospatial number coding. However, we need to bear in mind that in itself, the implication of a certain WM account for number-space associations does not specify whether the coding of the ordinal position of numbers in WM is visuospatial or verbal-spatial in nature (van Dijck, Ginsburg, Girelli, & Gevers, 2013). In other terms, the requirement of free visuospatial WM resources for the magnitude SNARC effect does not rule out the possibility that the underlying number coding strategy is (also) verbal-spatial in nature.

To complete the overall picture, it would be important to repeat our study with a number processing task that in itself is rather verbal in nature, such as the parity judgment task. Gevers et al. (2010) already found evidence for the predominance of verbal-spatial number coding when instructing participants to respond to the verbal labels “Left”/“Right” for odd/even digits. It would however be interesting to measure the relative contribution of verbal-spatial and visuospatial coding mechanisms in a spatial instruction condition to determine whether spatial instructions are sufficient to also activate visuospatial coding mechanisms in tasks that rely on verbal WM processes.

Finding evidence for the importance of task instructions in the underlying coding strategy of the SNARC effect also fits nicely with the study of Bächtold et al. (1998). They showed that the classically observed SNARC effect can be easily inverted when participants were previously instructed to imagine numbers as hours on a clock face (with small digits thus represented on the right hand-side and large digits on the left hand-side). Those findings thus clearly highlight the flexible nature of number-space associations and indicate that task instructions and settings not only affect the underlying coding mechanism of the SNARC effect, but also influence the directionality of a given number coding strategy (Fischer, 2006).

Finally, the emergence of visuospatial coding mechanisms under spatial instructions might have several underlying reasons. On the one hand, all participants might activate visuospatial coding in addition to verbal-spatial number coding, with both coding mechanisms thus contributing an equal extent to each individual's number-space associations. The resulting intra-personal conflict between the two coding systems in the spatial instruction condition would then provide an explanation for the appearance of a significantly negative visuospatial SNARC effect alongside an attenuation of the verbal-spatial SNARC effect (Figure 2B). Furthermore, when considering our word congruency analysis, it would also explain the lack of a significantly negative (or positive) SNARC regression slope on word incongruent trials (Figure 3B).

Another likely explanation is that despite the fact that all participants favour verbal-spatial coding under verbal instructions, number coding strategies might vary between individuals when put in an explicitly spatial context. Some individuals might completely switch to visuospatial number coding once put in the instruction-mediated spatial context (and thus yield the significantly negative visuospatial SNARC effect), while others might prefer verbal-spatial coding mechanisms even after receiving spatial instructions (and thus induce the significantly negative verbal-spatial SNARC effect). As such, the choice of coding strategy would not only depend on task instructions, but also on inter-individual variables. This latter explanation seems highly probable given that the strength of the SNARC effect is characterized by a considerable inter-individual variability and depends on factors such as gender (Bull et al., 2013), response speed (Cipora & Nuerk, 2013; Gevers et al., 2006), mathematical proficiency (Hoffmann, Mussolin et al., 2014), as well as age and inhibition capacities (Hoffmann, Pigat, & Schiltz, 2014). Moreover, Krause, Lindemann, Toni, and Bekkering (2014) have shown that the SNARC effect can be influenced by neural characteristics in the posterior parietal cortex, with increased grey matter volume in the right precuneus predicting stronger number-space interferences. These variables might thus not only affect the strength of an individual's number-space associations, but also determine their number coding strategies. Furthermore, the choice of coding strategy itself might have an effect on the strength of the SNARC effect, thereby providing an additional explanation for its high inter-individual variability. Georges, Hoffmann, and Schiltz (2014) have indeed shown that a certain cognitive style and thus possibly also a preference for a certain number coding strategy influences the strength of the SNARC effect in a magnitude comparison task. To get a clearer picture of whether any of the aforementioned variables plays a crucial role alongside task instructions in determining the spatial code associated with numbers, we need to repeat our experiment with clearly defined study populations. Even though some of these variables are likely to play an additional role in shaping the cognitive nature of an individual's number-space associations, the absence of a significant gender effect already shows that the choice of coding strategy is not affected by gender. Moreover, our results suggest that at least under verbal instructions verbal-spatial number processing is the preferred coding strategy regardless of an individual's characteristics.

In conclusion, previous findings of the relative dominance of verbal-spatial over visuospatial coding mechanisms need to be interpreted with caution, since participants were potentially biased towards a verbal-spatial processing strategy by task instructions based on verbal-spatial labels. Completing the previously used paradigm by adding a spatial instruction condition was therefore a necessary step to overcome this confound. It enabled us to determine whether the spatial code associated with numbers is always predominantly of verbal-spatial nature or whether it changes with task instructions (i.e., context). In line with earlier results, we could confirm the predominance of verbal-spatial coding mechanisms under verbal task instructions. However, this pattern completely changed when participants were put in an explicitly spatial context. In the spatial instruction condition, visuospatial coding was additionally activated, with both coding mechanisms contributing to an equal extent to number-space associations. The present study thus clearly demonstrates that the cognitive origin of number-space associations does not always predominantly rely on verbal-spatial processing mechanisms, but that the spatial code associated with numbers is context-dependent. The previously reported lack of evidence for visuospatial number coding can thus indeed be attributed to the verbal nature of task instructions. Given the essential role of context in shaping number-space associations, it needs to be taken into account when investigating the cognitive nature of the tight link between numerical and spatial representations in the future.

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9 General Discussion

This thesis pursued two different yet related research goals. The first question was addressed in studies 1 and 2 and concerned the relations between number-space associations, as indexed by the parity SNARC effect, and mathematical abilities in elementary school children as well as math anxiety in adults. The second question was approached in studies 3 and 4 and focussed on the spatial coding mechanisms underlying number-space associations, such as the SNARC effect, in different contexts and individuals.

In the following sections, I will summarize and discuss the results of each study with regard to the outcomes of the other studies to integrate all the main findings into a more complete picture of how the spatial coding processes underlying number-space associations, such as the SNARC effect, relate to mathematical development. I will start by firstly discussing the more domain-specific studies 3 and 4, concerned with the spatial nature of the coding mechanisms underlying the SNARC effect, before moving towards studies 1 and 2, assessing how these spatial coding processes relate to math abilities and anxiety. Considering that studies 3 and 4 provided new insights regarding the spatial coding processes actually underlying the SNARC effect, it is important to discuss these findings first, before interpreting the relations between the SNARC effect and math skills as well as math anxiety reported in studies 1 and 2 respectively.

9.1 Number-Space Associations and their Underlying Cognitive Mechanisms

Studies 3 and 4 collectively showed that the spatial coding mechanisms underlying the SNARC effect in adults depend on contextual factors such as the nature of the number processing task and the task instructions and are also influenced by inter-individual differences in cognitive variables such as arithmetic performances and visualization profile.

This thus provides strong evidence against the idea that all behavioural signatures of the strong connection between numbers and space, including the SNARC effect, might result from a single, predominant spatial coding account in all adults (e.g., Cheung et al., 2015). Conversely, it seems more likely that both visuospatial and verbal-spatial long-term representations as well as temporarily established associations between numbers and space in WM contribute to the full range of spatial-numerical interactions.

The contribution of multiple different spatial coding mechanisms to the SNARC effect depending on contextual and inter-individual factors can nicely rationalize the weaknesses that each of the proposed accounts bears in its potential to explain the entire range of spatial-numerical interactions. For instance, while the MNL is more difficult to reconcile with the flexible nature of number-space associations (e.g., Bächtold et al., 1998; Nathan et al., 2009; Shaki & Fischer, 2008), the verbal-spatial polarity account can hardly explain number-space associations in tasks without lateralized responses, such as the digit string bisection (Fischer, 2001) or random number generation task (Loetscher et al., 2008). The findings from studies 3 and 4 also complement previous observations regarding a multi-component solution when submitting the different behavioural effects commonly used to illustrate number-space associations to a principle component analysis (van Dijck et al., 2012). In addition, the heterogeneous nature of the cognitive processes underlying the SNARC effect agrees with studies indicating that both long-term spatial coding mechanisms such as the spatial representation of numerical magnitudes on the MNL and temporary associations between the ordinal position of numerical magnitudes and space in WM might exist in parallel (Ginsburg & Gevers, 2015; Huber et al., 2016; but see Abrahamse et al., 2016).

All in all, the observation that multiple different spatial coding mechanisms contribute to the SNARC effect depending on contextual and inter-individual factors highlights the robustness not only of this effect, but also of the association between numerical and spatial concepts in general. Numbers are likely associated with many different spatial codes that are not only visuospatial, but also verbal in nature. In addition, these associations are probably established both at a long-term and temporary level.

9.1.1 Inter-Individual Differences Determine the Task-Dependency of the Cognitive Mechanisms Underlying the SNARC Effect

Study 3 showed that the spatial coding mechanisms underlying the SNARC effect depend on the number processing task (i.e., implicit versus explicit numerical magnitude processing) and that the extent of this task-dependency is conditional upon inter-individual differences in cognitive variables such as arithmetic performances and visualization profile. In other terms, whether or not the spatial coding account explaining the SNARC effect varies intra-individually with task characteristics depends on inter-individual differences in the aforementioned cognitive factors.

The results revealed a positive correlation between the parity and magnitude SNARC effects in object-visualizers with lower arithmetic performances. Conversely, the two SNARC effects correlated negatively in spatial-visualizers with higher arithmetic performances. This thus suggests the predominance of a single spatial coding account for both implicit and explicit SNARC effects in the two types of visualizers or at least indicates the activation of task-dependent spatial coding processes that interact however either positively or negatively depending on visualization preferences. No relation was observed in mixed-visualizers, highlighting the activation of completely unrelated task-specific spatial coding mechanisms.

Unfortunately, the present study was not designed in a way that it could directly reveal the exact spatial nature of the coding processes underlying the SNARC effect in each of the number processing tasks and in every type of individual. Nonetheless, the relations of the parity and magnitude SNARC effects with the different numerical and spatial factors included in this study (i.e., arithmetic performances, spatial visualization ability, and visualization profile) enabled us to speculate about the different spatial coding mechanisms potentially contributing to each of the different effects at least at the population level.

The significant correlation between the magnitude SNARC effect and visualization profile suggests that the SNARC effect in explicit number processing tasks might arise from visuospatial rather than verbal-spatial coding mechanisms. It is, however, unclear whether these visuospatial processes involve the activation of numerical magnitudes on a long-term spatially oriented MNL or within a left-to-right oriented spatial sequence temporarily stored in WM[4]. Moreover, even both of these coding mechanisms might contribute to the magnitude SNARC effect, considering that they are probably not mutually exclusive (e.g., Huber et al., 2016). The importance of visuospatial coding processes for the SNARC effect in explicit tasks has been previously reported in that a visuospatial WM load was sufficient to abolish the magnitude SNARC effect (van Dijck et al., 2009; see also Herrera et al., 2008). Moreover, relying on a left-to-right oriented spatial representation of numerical magnitudes seems intuitive in tasks involving explicit magnitude processing, especially if numerical magnitudes need to be compared to a certain referent (e.g., 5), since categorizing digits visuospatially as left (smaller than 5) and right (larger than 5) might be helpful for successful task completion.

Conversely, the parity SNARC effect might not depend on such visuospatial coding processes at least in the majority of adults, considering the absence of a correlation between the latter effect and visualization preferences at the population level. The parity SNARC effect might thus rather arise from verbal-spatial coding mechanisms in most individuals in that it results from the congruency between the verbal polarity codes established at the stimulus and response levels (i.e., the association between the verbal categorical labels “small”/“left” and “large”/“right”). This might not seem surprising, given the rather verbal nature of the parity judgment task (i.e., labelling a digit as odd versus even is a typically

[4] I refer to the WM account as a “visuospatial” coding mechanism regardless of whether the numerical content stored in WM is of visuospatial or probably rather verbal nature, since it is based on attentional scanning along a left-to-right oriented spatial sequence temporarily stored in WM, similarly to the visuospatial shifts of attention along the MNL.

verbal task; see Gevers et al., 2010). Moreover, van Dijck et al. (2009) previously reported that the parity SNARC effect critically depended on the availability of verbal WM resources, probably required for such verbal-spatial polarity coding.

Importantly, these speculations about the spatial coding accounts potentially underlying the SNARC effects in implicit and explicit magnitude processing tasks are made based on observations across the entire study population. However, since the results clearly showed that the spatial nature of the underlying coding mechanisms depends on inter-individual differences in arithmetic performances and visualization profile, the parity and magnitude SNARC effects unlikely arise from verbal-spatial and visuospatial coding processes respectively in every individual. To get a better understanding of the specific spatial nature of the coding processes underlying the parity and magnitude SNARC effects in the different types of individuals, one needs to repeat some of the analyses while only focussing on a particular cognitive profile. One might for instance determine which numerical and spatial factors correlate with the parity and magnitude SNARC effects only in spatial-visualizers and whether different variables are related to these effects in object-visualizers.

Nonetheless, we can hypothesize about the spatial coding accounts potentially underlying the different SNARC effects in each type of individual. Considering that the parity and magnitude SNARC effects correlated in both object- and spatial-visualizers, both types of visualizers seem to activate a single predominant (or at least related) spatial coding mechanism(s) regardless of the implicit or explicit nature of the task. However, since positive and negative correlations between the two SNARC effects were observed in object- and spatial-visualizers respectively, the spatial nature of these coding processes likely varies between the latter types of individuals. In other terms, object-visualizers seem to rely on a different predominant spatial coding account than spatial-visualizers. This assumption can be supported by the correlation analyses. The parity and magnitude SNARC effects correlated with different numerical and spatial factors at the population level (i.e., the magnitude SNARC effect with visualization profile versus the parity SNARC effect with arithmetic performances). If the two kinds of visualizers activated the same predominant spatial coding process, such a clear distinction between the cognitive variables associated with the parity and magnitude SNARC effects might not have been evidenced in the entire population.

Interestingly, supplementary analyses revealed that spatial-visualizers featured on average stronger magnitude SNARC effects than object-visualizers[5] (see also Georges, Hoffmann, & Schiltz, 2014). Considering that more pronounced magnitude SNARC effects were associated with greater spatial visualization preferences (i.e., stronger reliance on visuospatial processing resources in the right parietal lobe; Lamm, Bauer, Vitouch, & Gstättner, 1999), it is likely that the magnitude and consequently also the parity SNARC effects in spatial-visualizers resulted from such visuospatial coding mechanisms involving the MNL and/or WM. The assumption that the stronger magnitude SNARC effects in spatial-visualizers resulted from visuospatial as opposed to verbal-spatial coding mechanisms also agrees with the results of study 4, indicating that visuospatial coding induced a more pronounced magnitude SNARC effect under spatial instructions than the verbal-spatial account. Given the negative correlation between the two SNARC effects in spatial-visualizers, the results then also suggest that greater reliance on such visuospatial coding mechanisms is associated with weaker parity SNARC effects. How might stronger visuospatial coding lead to less pronounced SNARC effects in the parity judgment task? One possibility is that spatial-visualizers activate numerical magnitudes both on a long-term spatially oriented MNL and within a spatial sequence temporarily stored in WM during task completion, considering that these accounts are not mutually exclusive (e.g., Ginsburg &

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[5] A one-way ANOVA on the magnitude SNARC effect regression slopes including visualization profile (object-visualizers versus spatial-visualizers) as between-subject variable revealed a tendency for a significant effect ($F(1, 80) = 3.5$, $p = .06$, $\eta p2 = .04$), with stronger magnitude SNARC effects in spatial-visualizers (slope = -7.79, *SD* = 12.11) than object-visualizers (slope = -2.42, *SD* = 13.71). Object- and spatial-visualizers were defined based on positive and negative differences between object and spatial scale z-scores respectively.

Gevers, 2015; Huber et al., 2016). While numerical magnitudes might be activated in their canonical order in WM in the magnitude classification task, manifesting in strong magnitude SNARC effects, this might not be the case in the parity judgment task. Since individuals are required to give left-/right-sided responses depending on whether digits are odd/even in the latter task, numerical magnitudes might be temporarily encoded in WM according to their parity status. This would then lead to strong MARC effects (i.e., faster left-/right-sided responses for odd/even digits respectively; see also Nuerk et al., 2004), but could potentially diminish the regular parity SNARC effect. The absence of the classical parity SNARC effect was for instance evidenced, when individuals had to memorize number sequences in descending order (Lindemann et al., 2008). Greater reliance on WM might thus lead to stronger magnitude SNARC effects, because numerical magnitudes are activated in their canonical order in WM. Conversely, it might entail weaker parity SNARC effects, because digits are temporarily memorized according to their parity status, which interferes with the long-term left-to-right spatial representation of numerical magnitudes on the MNL. The involvement of WM in the SNARC effect in spatial-visualizers might be supported by studies showing that spatial-visualizers are highly flexible in their strategy use (Pitta-Pantazi, Sophocleous, & Christou, 2013) and that cognitive flexibility is associated with stronger WM (Blackwell, Cepeda, & Munakata, 2009). In general, the assumption that spatial-visualizers rely on visuospatial coding processes involving the activation of numerical magnitudes at precise spatial positions either on the MNL or within WM and do not globally associate numerical magnitudes with verbal categorical labels agrees with studies reporting that spatial-visualizers preferentially encode and process stimuli analytically, part by part, using spatial relations to arrange and analyze the components (Kozhevnikov et al., 2005). Moreover, such a piecemeal, analytic processing style is also commonly reported in mathematically gifted individuals (Singh & O'Boyle, 2004).

Contrary to spatial-visualizers, individuals with object visualization preferences then likely relied on verbal-spatial coding mechanisms in both implicit and explicit tasks, if we assume that different spatial coding accounts were activated depending on the type of visualizer. The idea that numbers are simply verbally categorized as either small or large in the latter individuals is also in accordance with observations that object-visualizers tend to encode images globally as a single perceptual unit, which they process holistically (Kozhevnikov et al., 2005). Moreover, since we did not include any measures to determine the participants' verbal cognitive styles (Blazhenkova & Kozhevnikov, 2009), some individuals featuring greater object visualization preferences in the present study might actually be verbalizers. This assumption is based on findings showing a clear negative correlation between the spatial and verbal scale scores of the Object-Spatial Imagery and Verbal Questionnaire, but not between object and verbal scores (Blazhenkova & Kozhevnikov, 2009; Haciomeroglu, 2016). It might thus be interesting to also repeat the present study with verbalizers.

Finally, with respect to mixed-visualizers, it is highly probable that verbal-spatial and visuospatial coding mechanisms accounted for their parity and magnitude SNARC effects respectively, considering that the two SNARC effects were unrelated in these individuals as well as the observation that only the magnitude SNARC effect was associated with visualization profile at the population level. Interestingly, while previous research already suggested that both long-term spatial representations of numerical magnitudes on the MNL and temporary associations between numerical magnitudes and spatial positions in WM might exist in parallel (Ginsburg & Gevers, 2015; Huber et al., 2016; Lindemann et al., 2008), the present results extent these findings by indicating that different long-term accounts based on the association of numerical concepts with either visuospatial or verbal-spatial codes might also co-exist in the same individual.

On another note, considering the stronger magnitude SNARC effects in spatial- than object-visualizers and the assumption that these two types of visualizers likely relied on different spatial coding accounts, the present findings suggest that the spatial nature of the coding processes underlying the SNARC effect could be another factor explaining the well-documented inter-individual differences in its strength (e.g., Cipora et al., 2016; Hoffmann, Mussolin et al., 2014; Hoffmann, Pigat et al., 2014, Viarouge et al., 2014). More specifically, the reliance on visuospatial and verbal-spatial coding mechanisms in spatial-visualizers with higher arithmetic performances and object-visualizers with lower arithmetic performances respectively might account for the stronger parity SNARC effects sometimes reported in the latter population (e.g., Cipora et al., 2016; Hoffmann, Mussolin et al., 2014; but see Cipora & Nuerk, 2013). However, it remains to be determined whether spatial- and object-visualizers actually rely on visuospatial and verbal-spatial coding processes respectively and also whether the verbal-spatial account induces stronger parity SNARC effects.

All in all, the present findings highlight considerable inter-individual differences in the co-variance of the parity and magnitude SNARC effects and as such in the relatedness of their underlying spatial coding mechanisms. While some individuals seem to associate numerical concepts with spatial codes of varying nature (e.g., mixed-visualizers), others activate a single (or at least strongly related) spatial coding mechanism(s) independently of context. Such inter-individual variations in the spatial nature of the codes associated with numerical concepts conforms nicely to the well-documented inter-individual differences in the strategies used to tackle numerical problems (e.g., Chrysostomou et al., 2013; Grabner et al., 2007; Pitta-Pantazi et al., 2013). Moreover, it might explain some of the previously reported inconsistencies in the literature regarding the predominance as well as the specific spatial nature of the coding mechanisms underlying number-space associations, such as the SNARC effect (e.g., Cheung et al., 2015; Gevers et al., 2010; van Dijck et al., 2009, 2012).

9.1.2 Task Instructions Determine the Visuospatial and Verbal-Spatial Nature of the Cognitive Mechanisms Underlying the Magnitude SNARC Effect

The context-dependency of the spatial coding mechanisms underlying the SNARC effect was further highlighted in ***study 4***. Namely, the spatial coding processes accounting for the SNARC effect in an adapted explicit magnitude processing task depended on the verbal and spatial nature of the task instructions. Importantly, this study was designed in a way that it could directly reveal the exact spatial nature (i.e., verbal versus visual) of the coding account(s) explaining the magnitude SNARC effect in each of the two instruction conditions.

To dissociate the confound of both verbal- and visuospatial coding mechanisms typically encountered in the classical SNARC paradigm (e.g., faster left-sided responses for small digits might result from an association either between the verbal concepts “small” and “left” or between small numerical magnitudes and the left side of physical space), we implemented the modified version of the magnitude classification task initially introduced by Gevers and colleagues (2010). In this version, the positions of the verbal labels “Left” and “Right” are randomly varied to appear on the left or right physical response sides, thereby creating word congruent trials (where the verbal labels “Left”/”Right” appear at their corresponding physical locations) and word incongruent trials (where the verbal labels “Left”/”Right” appear on the right/left physical response sides respectively). While the visuospatial account is predicted by an interaction between numerical magnitudes and physical response sides regardless of the associated verbal labels, the contribution of verbal-spatial coding mechanisms is indicated by an association between numerical magnitudes and the verbal response labels irrespective of their side of appearance. Participants were instructed to base their responses once on the verbal labels and once on the physical response sides.

Interestingly, verbal-spatial coding processes were predominantly activated under verbal task instructions, while both verbal- and visuospatial coding mechanisms simultaneously contributed to an equal extent to the magnitude SNARC effect under spatial task instructions. The simultaneous observation of both verbal- and visuospatial coding accounts under spatial instructions might be explained in two ways. On the one hand, both spatial coding mechanisms might be activated simultaneously and to an equal extent in *every individual* under spatial instructions. On the other hand, some individuals might completely (or at least partly) switch towards visuospatial coding processes once put in a rather spatial context, while the remaining participants might still predominantly activate verbal-spatial coding mechanisms even in the spatial instruction condition. This could then explain the simultaneous observation of both verbal- and visuospatial coding mechanisms at the population level under spatial instructions, without every individual needing to simultaneously rely on both spatial coding accounts. The latter explanation nicely conforms to the outcomes of study 3 regarding inter-individual differences in the context-dependency of the spatial coding mechanisms underlying the SNARC effect. As such, inter-individual differences in cognitive characteristics could determine the relatedness of the spatial coding accounts explaining the SNARC effect not only in different tasks but also under different instructions.

According to study 3, the magnitude SNARC effect likely resulted from verbal-spatial coding mechanisms in one of the two types of visualizers relying on a single predominant spatial coding account in both implicit and explicit tasks (probably object-visualizers). Since this verbal-spatial predominance was observed in the classical version of the magnitude classification task, not comprising any verbal labels and always consisting of spatial task instructions, it seems unlikely that these individuals might additionally or entirely activate visuospatial coding mechanisms in a modified version of this task comprising verbal labels under spatial instructions. Consequently, the latter individuals probably exclusively relied on verbal-spatial coding mechanisms also in the spatial instruction condition and as such regardless of task instructions.

Conversely, it is certainly possible that individuals who usually activate visuospatial coding mechanisms in the classical version of either only the magnitude classification task (e.g., mixed-visualizers) or both the magnitude and parity judgment tasks (probably spatial-visualizers) completely switch towards verbal-spatial coding in a modified version of the magnitude classification task comprising verbal labels, especially if they are additionally instructed to base their responses on these verbal labels (i.e., under verbal task instructions). Since verbal-spatial polarity coding might assist successful task completion in the latter instance (at least in the experimental block where one has to click on the “Left”/”Right” verbal labels for small/large digits respectively), it might be the spatial coding mechanism of choice even in individuals usually not relying on verbal-spatial coding processes (at least not in explicit tasks). However, under spatial instructions, these individuals could completely revert back to visuospatial coding mechanisms or at least additionally activate the latter processes despite the inclusion of the verbal labels. Especially mixed-visualizers might activate both verbal- and visuospatial coding accounts in the spatial instruction condition, since they don't seem to have a specific preference for either of these spatial coding processes (see study 3).

Even though it seems highly plausible that the relation between the spatial coding mechanisms underlying the magnitude SNARC effect under different tasks instructions depends on inter-individual differences in cognitive factors, this needs to be empirically tested. Furthermore, the specific nature of these cognitive characteristics should be revealed. In addition, this study could be repeated with the parity SNARC effect. Considering (1) the verbal nature of the parity judgment task (i.e., labelling a digit as odd versus even is a typically verbal task; see Gevers et al., 2010), (2) the fact that the parity SNARC effect depends on the availability of verbal WM (van Dijck et al., 2009) and (3) the results of study 3 showing no correlation between the parity SNARC effect and visualization profile at the population level, this effect likely arises from verbal-spatial coding mechanisms in the classical version of the task at least in most individuals. As such, it is highly probable that the inclusion of verbal labels together with verbal task instructions also predominantly activate verbal-spatial coding mechanisms. This was actually confirmed previously (Gevers et al., 2010). The inclusion of verbal labels might even suffice to mainly activate verbal-spatial polarity coding also under spatial instructions even in individuals usually predominantly relying on visuospatial coding processes in the classical parity judgment task (probably spatial-visualizers). Consequently, the spatial coding mechanisms underlying the parity SNARC effect (in this modified task comprising verbal labels) might always be of verbal nature regardless of task instructions. Nonetheless, it cannot be fully excluded that those individuals usually entirely relying on visuospatial coding mechanisms regardless of context (probably spatial-visualizers) might revert back to this visuospatial account (or at least additionally activate it) under spatial instructions despite the inclusion of the verbal labels.

9.1.3 Limitations

An important point worth mentioning here is that we did not directly assess the involvement of ***WM*** in the emergence of the SNARC effect(s) in studies 3 and 4.

In *study 3*, we should have included measures of visuospatial and/or verbal WM to assess their relations with the parity and magnitude SNARC effects at the population level. This could have provided some valuable information regarding the potential contribution of WM to the SNARC effects in implicit and/or explicit number processing tasks, at least in the entire population. Nonetheless, finding evidence for the involvement of verbal WM in future studies will not inform us about whether the SNARC effect results from the activation of numerical magnitudes within a spatial sequence temporarily stored in verbal WM (Antoine, Ranzini, Gebuis, van Dijck, & Gevers, 2016) or verbal-spatial polarity coding, since even the latter cognitive process might depend on the availability of verbal WM resources (Lipinski, Spencer, & Samuelson, 2010). WM might also be another moderator in the relation between the parity and magnitude SNARC effects in that individuals with greater WM preferentially rely on the WM account regardless of context. This assumption is based on observations suggesting that individuals with higher WM likely resort to problem solving strategies relying on this construct (Beilock & Decaro, 2007; Ramirez, Gunderson, Levine, & Beilock, 2013).

In *study 4*, the association of digits with the verbal response labels “Left” and “Right” rather than with the physical response sides clearly suggests the contribution of the verbal-spatial polarity coding account. Conversely, associating small/large digits with the left/right physical response sides respectively regardless of the verbal response labels can be explained by the activation of numerical magnitudes either on a long-term spatially oriented MNL or within a spatial sequence temporarily stored in WM. Moreover, in the latter instance, it is unclear whether numerical magnitudes might be activated in visuospatial or verbal WM, since both were found to be involved in the emergence of the SNARC effect (van Dijck et al., 2009). Consequently, no firm conclusions can be drawn regarding the actual spatial nature of this “visuospatial” coding account that is additionally activated in the modified magnitude classification task under spatial instructions, since it might be the MNL or the WM account.

One possibility to determine whether the MNL or WM underlies the “visuospatial” magnitude SNARC effect under spatial instructions is to use a similar paradigm than the one administered in the study of van Dijck and Fias (2011), consisting of an encoding, classification and control phase (see also Ginsburg & Gevers, 2015; Huber et al., 2016). In the encoding phase, participants would be required to memorize a sequence of randomly ordered digits. The classification phase would then comprise the modified magnitude classification task including the verbal response labels and individuals would have to respond only to the digits included in the to-be-memorized sequence. Finally, in the control phase, participants would need to single out the to-be-memorized sequence from five alternatives. In this way, the simultaneous observation of both a “visuospatial” magnitude SNARC effect (i.e., faster left-/right-sided responses for small/large digits respectively) and an ordinal position effect (i.e., faster left-/right-sided responses for digits from the beginning/end of the to-be-memorized sequence respectively), irrespective of the verbal response labels, would indicate that the MNL most likely accounted for the “visuospatial” magnitude SNARC effect under spatial instructions, since loading WM with a randomly ordered sequence did not affect the emergence of the classical magnitude SNARC effect. Conversely, the absence of a regular “visuospatial” magnitude SNARC effect in the case where individuals needed to memorize a numerical sequence not following the inherent ordinal structure of the number system would rather suggest that the visuospatial coding mechanisms additionally activated under spatial instructions reflected the activation of numerical magnitudes within a spatial sequence temporarily stored in WM.

Another important point worth mentioning is that studies 3 and 4 were conducted in adults. It is therefore unclear whether different spatial coding accounts might also contribute to the SNARC effect ***in children*** depending on contextual factors and/or inter-individual differences in cognitive variables.

It is certainly possible that the SNARC effect results from a single predominant spatial coding account in all children regardless of context, simply because alternative spatial coding mechanisms might not have developed yet. Especially verbal-spatial polarity coding might only gradually arise with increasing language proficiency and the mastery of the verbal concepts “left” and “right” (see also Patro, Nuerk et al., 2016). On the other hand, the MNL could be innate (Bulf et al., 2015; Harvey et al., 2013) or at least quickly develop after birth due to cultural influences (e.g., Patro, Fischer et al., 2016) and as such exclusively account for all number-space associations evidenced at earlier developmental stages.

Since alternative spatial coding accounts might only gradually emerge over the course of development, age might be another moderator in the context-dependency of the spatial coding mechanisms underlying the SNARC effect. More specifically, the SNARC effects in implicit and explicit tasks might arise from a single spatial coding process in younger children, while multiple different spatial coding mechanisms might contribute to the parity and magnitude SNARC effects at later developmental stages due to the gradual emergence of alternative spatial coding processes such as verbal-spatial polarity coding. Nonetheless, study 3 highlighted the predominance of a single spatial coding account regardless of context even in some adults depending on their arithmetic performances and visualization profile. It is thus possible that individuals with certain cognitive characteristics never develop any alternative spatial coding mechanisms and therefore always exclusively depend on the same spatial coding process regardless of age. Consequently, the moderating effects of age on the relation between the parity and magnitude SNARC effects could be conditional upon the cognitive variables also determining the spatial nature of the coding processes underlying the SNARC effect in adults (i.e., arithmetic performances and visualization profile). This corresponds to a moderated moderation, where arithmetic performances and/or visualization profile determine whether age affects the relation between the spatial coding processes underlying the SNARC effect under different circumstances.

9.2 Number-Space Associations and their Relations to Math Abilities and Anxiety

9.2.1 The Parity SNARC Effect Relates to Arithmetical Abilities in Younger Children

Study 1 showed that stronger parity SNARC effects were associated with better arithmetical but not visuospatial math abilities, but only in the relatively younger third to fourth grade elementary school children. We explained these differential relations by suggesting that different strategies might be used to solve different math tasks at different development stages. Accordingly, a strategy based on the spatial coding processes underlying number-space associations, such as the parity SNARC effect, is likely adopted only in arithmetical tasks at earlier stages of mathematical development.

In the article, we argued that this strategy probably relies on the activation of numerical magnitude representations on a spatially oriented MNL Nonetheless, since study 3 showed that the spatial nature of the coding processes underlying the parity SNARC effect depends on arithmetic performances and visualization profile, this effect unlikely arises from the MNL in every individual. Consequently, the activation of numerical magnitudes on this long-term visuospatial construct might not exclusively account for the relation between stronger parity SNARC effects and better arithmetical abilities in the younger children. Moreover, the parity SNARC effect can only be considered as a more appropriate measure for indexing the properties of the MNL (than for instance bounded number line estimation performances) in those individuals actually activating spatial-numerical mappings on this mental medium. Conversely, in people rather relying on verbal-spatial polarity coding or the activation of numerical magnitudes within a spatial sequence temporarily stored in WM, the parity SNARC effect should not be preferentially assessed to make inferences about the specific importance of the MNL for mathematical development.

It is, however, still unclear whether the inter-individual differences in the spatial coding mechanisms underlying the parity SNARC effect in adults also apply to children and as such whether spatial coding accounts other than the MNL should be considered in the interpretations of the present findings. After all, the parity SNARC effect could entirely result from the MNL at earlier developmental stages. As already argued before, not all the spatial coding accounts proposed in adults might be suitable to explain number-space associations, such as the parity SNARC effect, in children. Especially the verbal-spatial account might only emerge later in life as it relies on the use of spatial language. Even though English-speaking children already start to develop spatial language at the age of 2, mastery takes a couple of years (Kuczaj & Maratsos, 1975; Johnston, 1984; Sowden & Blades, 1996). Moreover, it has been shown that while 5-year-old children already have adult-like mastery of the verbal concepts “front” and “back”, they still struggle with the concepts “left” and “right” (Kuczaj & Maratsos, 1975). Children usually only acquire egocentric left and right between the ages of 5 and 7 (Hermer-Vazquez et al., 2001). In addition, the ability to rely on the phonological system to verbally recode visually presented information only arises at the age of 8 years (Pickering, 2001). Children younger than this age are usually not able to generate verbal codes for visual stimuli and therefore solely rely on their visual storage processes. Accordingly, 5-year-old children were shown to still exclusively rely on spatial coding in spatial tasks, while a phonological approach was more commonly used only from 8 years onwards (Fenner et al., 2000; Palmer, 2000). Consequently, the verbal-spatial account might only arise at later developmental stages, such that all kinds of number-space associations might arise from visuospatial coding mechanisms in younger children. However, even if this is the case, it is unclear whether this visuospatial coding involves the activation of numerical magnitudes on a long-term spatially oriented MNL or within a spatial sequence temporarily stored in WM. The present results thus need to be discussed not only with regard to the MNL (as it is done in the article), but also in light of the WM account and possibly even with respect to verbal-spatial polarity coding.

Although this study does not allow us to draw any firm conclusions about the specific involvement of the MNL in the acquisition of math skills, interpreting the results with respect to all the different spatial coding mechanisms potentially accounting for the parity SNARC effect in adults will nonetheless advance our knowledge of the cognitive processes contributing to mathematical development. Moreover, it could potentially provide further information regarding the spatial coding account(s) actually underlying the parity SNARC effect in elementary school children. Before interpreting the relation between the parity SNARC effect and math skills also in light of the WM and verbal-spatial accounts, I will quickly re-capitulate the main characteristics of each of these spatial coding processes.

According to the WM account (Abrahamse et al., 2016; Fias et al., 2011, Fias & van Dijck, 2016; Ginsburg et al., 2014; van Dijck & Fias, 2011; van Dijck et al., 2014), task-relevant numerical magnitudes are activated in their canonical order within a horizontally left-to-right oriented spatial sequence temporarily stored in WM. This then leads to the SNARC effect via the association of numerical magnitudes from the beginning/end of the sequence with the left/right response side respectively. In this way, stronger SNARC effects are explained by the greater likelihood of activating such numerical magnitude information in WM.

According to the verbal-spatial account (Gevers et al., 2010; Proctor & Cho, 2006; see also the neural network model proposed by Gevers et al., 2006), numerical magnitudes are associated with the verbal categorical labels “small” and “large”. In binary classification tasks, such as the SNARC paradigm, such verbal categorical codes are also assigned to the two response alternatives “left” and “right”. The congruency between the polar codes on the stimulus and response dimensions (i.e., “small”/“left” versus “large”/“right”) then leads to faster responses and thereby explains the SNARC effect. As such, more pronounced SNARC effects might result from the greater likelihood of associating numerical magnitudes with the verbal labels “small” and “large”.

With regard to the *WM account*, the positive relation between stronger parity SNARC effects and better arithmetical performances in the ***relatively younger children*** suggests that the activation of task-relevant numerical magnitudes within a spatial sequence temporarily stored in WM is involved in the successful completion of arithmetic tasks. This nicely agrees with studies highlighting the importance of WM-based procedural calculation strategies (e.g., transformation and/or counting) for arithmetic problem solving at earlier stages of mathematical learning, while the reliance on fact retrieval from long-term memory plays a greater role only at later developmental stages with increased math proficiency (Ackerman, 1988; Ashcraft, 1982; Geary et al., 2004; Grabner et al., 2007; Peng et al., 2016; Siegler, 1998). Moreover, activation of the dorsal basal ganglia and parietal cortex in arithmetic tasks was much higher in younger than older children, again indicating greater demands on procedural WM systems during earlier stages of math development (Qin et al., 2004; Rivera, Reiss, Eckert, & Menon, 2005). Conversely, the absence of a relation between the visuospatial math component and the parity SNARC effect indicates that solving visuospatial math problems does not rely on the storage of numerical information in WM. This is in line with the meta-analysis by Peng et al. (2016), reporting that math problems relying on spatial concepts, such as geometry, featured the weakest relation with WM (see also Giofrè, Mammarella, Ronconi, & Cornoldi, 2013).

Regarding the specific WM component involved in explaining the relation between stronger parity SNARC effects and better arithmetical abilities, McKenzie and colleagues (2003) reported a gradual age-related shift from the reliance on visuospatial WM towards the greater contribution of verbal WM during arithmetic problem solving. Namely, arithmetic performances of 7-year-old children were only affected by visuospatial WM disruption, while the performances of 9-year-olds were disrupted by both visuospatial and verbal interferences. Considering that the children in the present sample were aged between 8 and 11 years, verbal WM likely already contributed to arithmetic problem solving in most of the children. The involvement of verbal WM also agrees with the observation that the parity as opposed to the magnitude SNARC effect probably relies on verbal rather than visuospatial WM resources (van Dijck et al., 2009). The relation between the parity SNARC effect and arithmetical abilities can thus likely be explained by the activation of numerical magnitudes in verbal WM during the completion of arithmetic tasks. Considering that the magnitude SNARC effect rather depends on visuospatial WM resources, it might be interesting to determine how the latter effect relates to math abilities in the younger children. Nonetheless, since the study of van Dijck and colleagues (2009) was conducted in adults, it is unclear whether visuospatial and verbal WM differentially contribute to the SNARC effect depending on the implicit or explicit nature of the number processing task in children.

With regard to the *verbal-spatial account*, the relation between stronger parity SNARC effects and better arithmetical abilities in the relatively younger children seems more difficult to explain, since stronger associations of numerical magnitudes with the verbal categorical labels “small” and “large” might hardly beneficially affect arithmetic problem solving regardless of strategy use, i.e., independently of whether children rely on procedural calculation strategies or fact retrieval from long-term memory to complete arithmetic tasks. Neither of these strategies should benefit from such verbal categorical coding, since they both rely on exact quantity processing (e.g., Vanbinst, Ansari, Ghesquière, & De Smedt, 2016; Vanbinst, Ceulemans, Ghesquière, & De Smedt, 2015). Considering that children with better access to exact symbolic magnitude representations excel in both procedural strategies as well as fact retrieval (Vanbinst, Ghesquière, & De Smedt, 2012), simply approximating numerical magnitudes by verbally categorizing them as being either small or large should rather detrimentally affect arithmetic problem solving. Support for this idea is provided by findings from Lonnemann, Krinzinger, Knops, and Willmes (2008). They evidenced weaker arithmetic performances with stronger number-space associations especially in girls, who preferentially rely on a verbal thinking style during arithmetic problem solving. Conversely, a positive correlation between stronger spatial-numerical interactions and higher performances was revealed in boys, generally adopting a rather visuospatial strategy. The positive association between stronger parity SNARC effects and better arithmetical abilities in the relatively younger children thus suggests that the parity SNARC effect unlikely resulted from such verbal-spatial polarity coding at this earlier developmental stage (at least at the population level). This also conforms to the aforementioned assumption that the SNARC effect probably exclusively arises from visuospatial coding mechanisms based on either the MNL or WM in younger children. Interestingly, Imbo, Brauwer, Fias, and Gevers (2012) evidenced verbal-spatial coding in 9-year-old children. However, since they did not test children younger than this age, it is unclear whether verbal-spatial coding processes can be activated at even earlier stages of development. Van Galen and Reitsma (2008) suggested that verbal-spatial polarity coding might only start to develop and contribute to the SNARC effect from 9 years onwards, since the shape of the SNARC effect gradually changed from continuous to categorical at that age. Nonetheless, these studies focussed on the magnitude SNARC effect. In addition, children received verbal task instructions in the study of Imbo et al. (2012). It is therefore unclear whether and when the verbal-spatial account might underlie the SNARC effect in the classical parity judgment task.

Even though the parity SNARC effect probably entirely resulted from visuospatial coding mechanisms in the relatively younger children, verbal-spatial polarity coding might have contributed to the parity SNARC effect in the ***relatively older children***. The gradual age-related shift towards verbal-spatial coding processes could then also account for the moderating effects of age on the relation between the parity SNARC effect and arithmetical abilities. Nonetheless, considering the outcomes of study 3 regarding inter-individual differences in the spatial nature of the coding mechanisms underlying the parity SNARC effect in adults, it is unlikely that all the children started to rely on such verbal-spatial polarity coding with increasing age. Some individuals might predominantly activate numerical magnitudes either on a long-term spatially oriented MNL or within a spatial sequence temporarily stored in WM regardless of age. This potential heterogeneity of the spatial coding accounts underlying the parity SNARC effect in relatively older children might then explain the absence of a relation between the latter effect and arithmetical abilities at the population level. While positive associations between stronger parity SNARC effects and better arithmetical abilities might further be observed in children relying on either the MNL or WM in numerical tasks, negative relations might be evidenced in those children henceforth predominantly activating verbal-spatial polarity coding. This assumption is, however, only valid, if we assume that children still adopt procedural calculation strategies involving either the MNL or WM to solve arithmetic tasks. Although this might still be the case in some children, especially those with less proficient math skills (Berteletti, Prado, & Booth, 2014; Delazer et al., 2003; Grabner et al., 2007), studies suggest that children at that age generally start to rely on fact retrieval from long-term memory during arithmetic problem solving (Imbo & Vandierendonck, 2007). Most of the relatively older children might thus have switched from procedural calculations towards fact retrieval. Since retrieving facts from long-term memory might not rely (or at least to a lesser extent) on either WM (Hecht, 2002; Seyler, Kirk, & Ashcraft, 2003) or the spatial representation of numerical magnitudes on a long-term MNL (i.e., activation of angular gyrus for fact retrieval; Grabner et al., 2009 versus activation of IPS for the parity SNARC effect; Cutini et al., 2014; Rusconi et al., 2007, 2013), no relation between the parity SNARC effect and arithmetical abilities should be observed in those children relying on fact retrieval during arithmetic problem solving, but activating numerical magnitudes either on the MNL or within WM in numerical tasks. This idea can be supported by the study of Link et al. (2014), reporting that number line estimation performances related more strongly to addition and subtraction than multiplication skills, probably because the resolution of multiplication problems is solely based on fact retrieval rather than procedural calculations (Dehaene et al., 2003). Considering the irrelevance of activating numerical magnitudes either on the MNL or within a spatial sequence temporarily stored in WM for arithmetic problem solving via fact retrieval, such spatial-numerical associations might even negatively affect math performances due to their potential interference with optimal fact retrieval. This might especially be the case in adults and will be discussed in greater detail in the next section where the relation between the parity SNARC effect and math anxiety will be considered. A negative relation between stronger parity SNARC effects and weaker arithmetical abilities might also be evidenced in children (and adults) activating verbal-spatial polarity coding in numerical tasks, but relying on fact retrieval to complete arithmetic problems. As already argued before, verbal coding might not have any beneficial (but rather detrimental) effects on math problem solving regardless of whether individuals rely on procedural calculations or fact retrieval in arithmetic tasks.

In summary, the positive relation between stronger parity SNARC effects and better arithmetical but not visuospatial math abilities in the relatively younger children suggests that children at earlier developmental stages likely rely on procedural calculation strategies involving the activation of numerical magnitudes either on a long-term spatially oriented MNL or within a spatial sequence temporarily stored in (verbal) WM to solve arithmetic but not visuospatial math problems. Considering that verbal-spatial polarity coding might be hardly beneficial for arithmetic problem solving regardless of strategy use, the results also indicate that the parity SNARC effect unlikely resulted from verbal-spatial coding mechanisms at that earlier stage of development. This thus provides valuable information with regard to the developmental trajectory of the spatial coding mechanisms potentially underlying the parity SNARC effect. A shift towards either fact retrieval from long-term memory during arithmetic problem solving and/or the reliance on verbal-spatial coding processes in some but not all of the relatively older children might then account for the null relation between the parity SNARC effect and arithmetical abilities at the population level at later developmental stages.

All in all, considering the relation between the parity SNARC effect and arithmetical abilities in younger children, the parity SNARC effect might be used as an additional index to screen for individuals at risk of developing math learning difficulties, at least at earlier stages of math development. However, since the reliability of the SNARC effect in the classical parity judgment setup is usually relatively low (Viarouge et al., 2014; see also Wood, Nuerk, & Willmes, 2006; study 3), repetitions of each digit per condition need to be increased to ensure that the parity SNARC effect reliably indexes the strength of spatial-numerical interactions (see Cipora & Nuerk, 2013; Cipora & Wood, 2012). Since this entails quite lengthy testing sessions, it remains to be seen whether the parity judgment task can actually be implemented as an additional test to identify atypically developing children.

On another note, strengthening number-space associations through training might be beneficial for arithmetical but not visuospatial math problem solving in younger children prior to grade 4. As a concrete example, children could be trained on a magnitude classification task where they respond via moving to the left/right field on a dance map if the displayed target number is smaller/larger than a given standard respectively (Fischer, Moeller, Bientzle, Cress, & Nuerk, 2011). Spatial-numerical interactions might also be strengthened by training children on a modified version of the number line estimation task, where they walk along a number line taped to the floor towards the estimated position of a given target number (Link et al., 2013; see also Fischer et al., 2015).

Although such embodied training interventions could be beneficial in younger children, they might not affect math problem solving at later developmental stages, since older children probably no longer rely on procedural calculation strategies based on spatial-numerical mappings but rather on fact retrieval from long-term memory to solve arithmetic tasks. Strengthening number-space associations at these later developmental stages might even detrimentally relate to arithmetic performances on the basis of exacerbating the interferences of such spatial-numerical mappings with fact retrieval. But then again, number-space associations, such as the parity SNARC effect, probably predominantly result from verbal-spatial polarity coding in the majority of older children. Considering that embodied training paradigms are based on physical space and that verbal-spatial polarity coding rather involves conceptual space tightly linked to language, full-body training might not affect, let alone strengthen, the verbal-spatial coding mechanisms underlying number-space associations at these later developmental stages. Consequently, the risk that embodied training in older children might negatively affect their math skills seems minimal and the training might only be redundant.

In any case, since older children probably rely on fact retrieval as opposed to procedural calculations involving spatial-numerical mappings during arithmetic problem solving, training at these later developmental stages should rather focus on inhibiting number-space associations, especially in tasks where the activation of the spatial codes associated with numerical magnitudes is irrelevant for successful task resolution. Possible training paradigms might thus concentrate on strengthening an individual's capacity to ignore and filter out irrelevant stimulus-intrinsic spatial features. To give a concrete example, one might implement the incompatibility task presented in study 2, requiring individuals to make binary color judgments on centrally presented arrows pointing either towards the left or right. Children might then be trained on this task via progressively increasing the difficulty to ignore the irrelevant spatial pointing directions of the arrows. This could be achieved by continuously enhancing distractor salience through increasing the size of the arrows.

9.2.2 The Parity SNARC Effect Relates to Math Anxiety in Adults

Study 2 showed that stronger parity SNARC effects were associated with greater math anxiety in adults and that the parity SNARC effect explained variance in the latter affective variable over and above arithmetic performances, visuospatial WM, and inhibitory control. Stronger reliance on spatial aspects when dealing with numerical magnitudes (i.e., more pronounced parity SNARC effects) might thus lead to greater math anxiety, possibly via negatively affecting math performances (Cipora et al., 2016; Hoffmann, Mussolin et al., 2014; see also relations between stronger parity SNARC effects and weaker arithmetic performances reported in studies 2 and 3).

Considering inter-individual differences in the spatial coding mechanisms underlying the parity SNARC effect in adults (see study 3), the relation between stronger parity SNARC effects and greater math anxiety might not be exclusively explained by a single spatial coding account (e.g., MNL). In the next sections, I will therefore discuss the present findings in light of all the different spatial coding processes suggested to underlie the parity SNARC effect in adults. Special emphasis will be put on the relation between the parity SNARC effect and math performances, assuming that math skills likely mediate the relation between the parity SNARC effect and math anxiety (Ashcraft & Kirk, 2001; Ashcraft & Moore, 2009; Cipora et al., 2016; Hembree, 1990; Hoffmann, Mussolin et al., 2014; Ma, 1999; Ma & Xu, 2004).

With regard to visuospatial coding processes involving either the MNL or WM, the association between stronger parity SNARC effects and weaker math skills/greater math anxiety might be explained as follows: altered spatial-numerical mappings on the MNL or within WM might not only manifest in stronger parity SNARC effects, but could also prevent individuals from adopting more efficient problem solving strategies, such as fact retrieval from long-term memory, during the completion of arithmetic tasks (Berteletti et al., 2014; De Smedt, Holloway, & Ansari, 2011). Greater reliance on suboptimal alternative strategies, probably based on procedural calculations involving the activation of numerical magnitudes either on the spatially oriented MNL or within a spatial sequence temporarily stored in WM, during arithmetic problem solving would then negatively affect math performances (e.g., Grabner et al., 2007), ultimately leading to the emergence of math anxiety.

Nonetheless, the assumption that greater reliance on procedural calculations involving the MNL during math problem solving accounted for the weaker math skills/greater math anxiety in individuals with stronger parity SNARC effects cannot be supported by the present data. Namely, the absence of a relation between math performances and the distance effect suggests that individuals unlikely relied on procedural calculations based on spatial-numerical representations on the MNL to solve arithmetic problems. This argumentation is, however, only valid, if we assume that the distance effect actually reflects the extent of representational overlap on the MNL, since it was also suggested to result from response-related comparison processes (van Opstal et al., 2008).

The present outcomes also question the idea that greater reliance on WM-based procedural calculations during the completion of math tasks might explain the weaker math skills/greater math anxiety in individuals with more pronounced parity SNARC effects. Since visuospatial

WM was positively and not negatively associated with math performances, WM-mediated calculation processes rather supported than hindered math problem solving. WM is, however, also involved in fact retrieval, albeit to a much lesser extent than in procedural calculations (Imbo & Vandierendonck, 2007). The positive association between stronger WM and better math skills might thus simply reflect greater reliance on fact retrieval.

The aforementioned observations thus collectively suggest that individuals probably rather relied on fact retrieval from long-term memory than on procedural calculations involving either the MNL or WM during arithmetic problem solving. A more likely alternative explanation for the relation between stronger parity SNARC effects and weaker math skills/greater math anxiety might thus be as follows: although individuals relied on fact retrieval from long-term memory to solve arithmetic problems, they still activated numerical magnitudes either on a long-term spatially oriented MNL or within a spatial sequence temporarily stored in WM during task completion. Considering the irrelevance of such spatial-numerical mappings for efficient fact retrieval (Cutini et al., 2014; Grabner et al., 2009; Hecht, 2002; Rusconi et al., 2007, 2013; Seyler et al., 2003; see also Link et al., 2014), the activation of the spatial codes either on the MNL or within WM probably interfered with the latter strategy during arithmetic problem solving. This then negatively affected math performances, causing the development of math anxiety. Since the inability to suppress spatial coding during the completion of numerical tasks might be ascribed to weaker inhibition capacities (Hoffmann, Pigat et al., 2014), especially individuals with lower inhibitory control might activate the irrelevant magnitude-associated spatial codes on the MNL or within WM during arithmetic problem solving, in turn suffering from the negative consequences (i.e., weaker math skills/greater math anxiety).

In general, the idea that altered activation of numerical magnitude representations on the MNL might account for the math difficulties ultimately leading to the emergence of math anxiety agrees with recent findings in the literature and also conforms to the view of some researchers regarding the origins of math anxiety. Maloney, Ansari, and Fugelsang (2011) for instance observed stronger distance effects in individuals with high versus low math anxiety (see also Dietrich et al., 2015), which led them to suggest that less precise numerical magnitude representations on the MNL might be a risk factor for math anxiety (but see van Opstal et al., 2008). Similar conclusions were drawn by Núñez-Peña and Suárez-Pellicioni (2014), reporting larger ERP distance effects in high than low math anxious individuals.

A closer look at the present data, however, suggests that altered numerical magnitude representations on the MNL unlikely accounted for the relation between stronger parity SNARC effects and greater math anxiety. Namely, the parity SNARC effect did not correlate with the distance effect, suggesting that the former probably resulted from spatial coding mechanisms other than the MNL (at least in the majority of participants). However, stronger distance effects were associated with higher math anxiety also in the present study. Consequently, the present findings cannot generally refute the idea that altered numerical magnitude representations on the MNL might contribute to math anxiety (e.g., Maloney et al., 2011; but see van Opstal et al., 2008). They merely suggest that the MNL did not explain the relation between stronger parity SNARC effects and greater math anxiety and as such did not primarily account for the emergence of math anxiety, considering that the parity SNARC effect was a stronger predictor of this affective variable than the distance effect.

Although the MNL did probably not underlie the parity SNARC effect (at the population level), it is also unclear whether the activation of numerical magnitudes within a spatial sequence temporarily stored in WM accounted for it and as such could explain the relation between stronger parity SNARC effects and greater math anxiety. Despite the significant correlation between the parity SNARC effect and (visuospatial) WM, weaker WM related to stronger parity SNARC effects. However, if the parity SNARC effect actually resulted from the WM account, an association between weaker WM and less pronounced parity SNARC effects should have been evidenced. This assumption is based on the observation that the depletion of WM resources led to the absence rather than the strengthening of the SNARC effect (Ginsburg et al., 2014; Herrera et al., 2008; van Dijck et al., 2009).

The aforementioned findings thus suggest that the parity SNARC effect likely resulted from verbal-spatial polarity coding rather than the activation of numerical magnitudes either on the MNL or within WM in the majority of individuals. This agrees with study 3, indicating the absence of a correlation between the parity SNARC effect and visualization profile at the population level. Consequently, the association between stronger parity SNARC effects and weaker math skills/greater math anxiety might also be mainly explained by the verbal-spatial account. This is in line with the observation that the magnitude SNARC effect, associated with visualization profile at the population level and as such most likely arising from visuospatial coding mechanisms, was not related to arithmetic performances (see study 3) and as such might probably also not associate with math anxiety. However, this hypothesis regarding the magnitude SNARC effect needs to be tested (see limitation section below).

How can the relation between stronger parity SNARC effects and greater math anxiety be explained in light of the verbal-spatial account? One possibility is that a greater tendency to verbally categorize task-relevant numerical stimuli into opposing polarities based on their magnitudes during numerical tasks not only manifests in more pronounced parity SNARC effects, but also interferes with the strategies adopted during arithmetic problem solving (probably fact retrieval). This then negatively affects math performances, causing math anxiety. As mentioned before, especially individuals with weaker inhibitory control might fail to inhibit such irrelevant verbal coding in numerical tasks (Hoffmann, Pigat et al., 2014), subsequently suffering from weaker math skills/greater math anxiety. This idea thus stresses again the role of inhibitory control processes in the relation between stronger parity SNARC effects and the weaker math skills ultimately leading to greater math anxiety.

The critical contribution of inhibitory control has also been reported in previous studies. Hopko, McNeil, Gleason, and Rabalais (2002) for instance observed that individuals with high math anxiety required more time to indicate the quantity of numerical than non-numerical stimuli in a number Stroop task, whereas no differences in reaction times were observed in their low math anxious peers. Similarly, Pletzer, Kronbichler, Nuerk, and

Kerschbaum (2015) showed that the compatibility effect in a number comparison task was accompanied by higher neural activity in inhibitory control areas, such as the inferior frontal cortex, on incompatible trials for participants with low but not high math anxiety, thereby indicating an inhibitory deficit in the latter individuals. Moreover, in a task where individuals were required to respond to the digits with greater numerical magnitude while ignoring their irrelevant physical size, Suárez-Pellicioni, Núñez-Peña, and Colomé (2014) found a greater degree of interference for response speeds in the high compared to the low math anxiety group. These findings thus collectively suggest that individuals with high math anxiety have difficulties to suppress task-irrelevant information in interfering situations.

Nonetheless, it is unclear whether such inhibitory deficits are at the origin of greater math anxiety or merely one of its consequences. The majority of findings regarding the relation between inhibitory control and math anxiety were interpreted with respect to math anxiety causing greater distractibility rather than the reverse. The present results, however, indicate that math anxiety not only disrupts inhibition processes, as suggested in the deficient attentional control theory (Eysenck et al., 2007; extension of the processing efficiency theory proposed by Eysenck & Calvo, 1992; see also Hopko et al., 1998), but also likely results from inhibitory deficits in the first place. Especially the inability to efficiently suppress the association of numerical magnitudes with irrelevant verbal codes during number processing tasks might cause the math difficulties ultimately leading to math anxiety. This idea is based on the observation that the parity SNARC effect predicted math anxiety even when controlling for general inhibition capacities. Nonetheless, the assumption that math anxiety results from a specific deficit to inhibit irrelevant verbal coding of numerical magnitudes during math problem solving needs further investigation (see limitation section below).

On another note, although the verbal-spatial account probably explained the parity SNARC effect at the population level and therefore also predominantly accounted for the relation between stronger parity SNARC effects and greater math anxiety, the parity SNARC effect certainly resulted from either the MNL and/or WM processes in some individuals (see study

3). It thus remains to be determined whether the relation between the parity SNARC effect and math skills/anxiety depends on the spatial coding mechanisms underlying this effect. In other terms, it is unclear whether a certain spatial coding account, such as for instance verbal-spatial polarity coding, might more strongly relate to weaker math skills/greater math anxiety than the activation of numerical magnitudes either on a spatially oriented MNL or within a spatial sequence temporarily stored in WM. The relation between the parity SNARC effect and math skills/anxiety might thus be conditional upon the cognitive variables also determining the spatial nature of its underlying coding processes (i.e., visualization profile and arithmetic performances; see study 3). If we follow this line of thought, the spatial coding account explaining the parity SNARC effect might differ between individuals with high versus low math anxiety. This could then also explain the between-group differences in the strength of the parity SNARC effect, if we assume that the size of this effect depends on the spatial nature of its underlying coding account. At least, the latter idea might be supported by the outcomes of study 3, indicating weaker magnitude SNARC effects in object- than spatial-visualizers who likely differed with regard to the spatial coding mechanisms underlying their SNARC effects (see also Georges et al., 2014).

A final point worth bearing in mind is that assessing the relation between the parity SNARC effect and math anxiety in adults does not allow us to draw any firm conclusions about whether altered spatial-numerical mappings might actually be at the origin of math anxiety and thereby represent a risk factor for its development. Such conclusions can only be made from the current findings under the conditions that (1) the size of the parity SNARC effect, as it is measured in the present adult population, is indicative of its strength at the time math anxiety first emerges and (2) the association between the parity SNARC effect and math performances remains negative from the time math anxiety starts to develop until adulthood, assuming that math skills mediate the relation between the parity SNARC effect and math anxiety. Unfortunately, it is still unclear whether the strength of the parity SNARC effect remains constant throughout development. Interestingly, some studies suggested that its size might decrease with age (e.g., Berch et al., 1999). Conversely, Hoffmann, Pigat et al. (2014) reported stronger parity SNARC effects in the elderly compared to young adults (see also Ninaus et al., manuscript submitted for publication; Wood, Willmes, Nuerk, & Fischer, 2008). Contrary to the size of the parity SNARC effect, study 1 clearly showed that a negative association between stronger parity SNARC effects and weaker math skills probably only develops after grade 4. As such, math anxiety needs to emerge at least after this developmental stage, in case the cognitive processes underlying the parity SNARC effect represent a risk factor for its emergence. Moreover, if it is especially the inability to supress the association of numerical magnitudes with irrelevant verbal codes during arithmetic problem solving that negatively affects math performances, ultimately leading to greater math anxiety, the latter affective variable needs to emerge after individuals start to rely on such verbal-spatial polarity coding at the age of about 8 years (Imbo et al., 2012; Pickering, 2011; van Galen & Reitsma, 2008). Even though research on math anxiety mostly focussed on older children, indicating that it peaks at about grade 9 (Hembree, 1990), a few studies in younger children reported that math anxiety develops quite early in childhood between the ages of 6 and 9 (Krinzinger, Kaufmann, & Willmes, 2009; Ramirez et al., 2013; Wu et al., 2012). In that case, the spatial coding mechanisms underlying the parity SNARC effect probably only contribute to greater math anxiety in adolescence and adulthood without representing one of the risk factors for its emergence in the first place. This does, however, not undermine the role of these cognitive processes in influencing an individual's level of math anxiety at later developmental stages. Nonetheless, future studies should investigate whether and how the parity SNARC effect relates to math anxiety when this affective variable first arises in 6-year-olds (e.g., Krinzinger et al., 2009).

9.2.3 Limitations

First of all, it is important to mention that we did not assess the ***causality*** of the relations between the parity SNARC effect and either math abilities in elementary school children or math anxiety in adults. The present results are all correlational in nature and as such no firm causal conclusions can be drawn. Even though we interpreted the findings from studies 1 and 2 with regard to the spatial coding mechanisms underlying the parity SNARC effect affecting arithmetical abilities in younger children as well as math anxiety in adults, reverse relations cannot be fully excluded. More specifically, it might be possible that better arithmetical abilities in elementary school children and greater math anxiety in adults both lead to stronger parity SNARC effects.

In *study 1*, more efficient reliance on procedural calculations during arithmetic problem solving in the relatively younger children might not only manifest in better arithmetic performances at that particular developmental stage, but also sharpen and refine the underlying numerical magnitude representations (see Cipora et al., 2015), leading to more pronounced parity SNARC effects. The representation of numerical quantities is actually shown to undergo such developmental modifications in that it changes from logarithmic to linear in children between Kindergarten and fourth grade (Booth & Siegler, 2006, 2008; Geary et al., 2007; Laski & Siegler, 2007; Siegler & Booth, 2004). Importantly, this representational shift depends on numerical experiences and formal education. For instance, the Munduruсu, an Amazonian indigene group with a reduced numerical lexicon and little formal education, mapped numerical magnitudes onto a logarithmic scale, while Western adults used a linear mapping (Dehaene, Izard, Spelke, & Pica, 2008). In addition, practicing numerical abilities increased the acuity of numerical representations in children with math learning difficulties (Wilson, Revkin, Cohen, Cohen, & Dehaene, 2006). Cardinality proficiency and symbolic number knowledge also predicted non-symbolic number comparison performances (Mussolin, Nys, Content, & Leybaert, 2014). These findings thus suggest that symbolic number skills are important precursors in the developmental refinement of approximate number representations. Consequently, more advanced arithmetic strategies and procedures might also affect the mapping of symbolic numerical magnitudes on the MNL. A two-way relation between the parity SNARC effect and arithmetical abilities might thus be possible in that arithmetical skills initially strengthen and refine basic spatial-numerical representations, which then in turn beneficially affects arithmetic performances in a sort of feedback loop. Nonetheless, this idea is only valid if the parity SNARC effect results from the activation of numerical magnitude representations on a spatially oriented MNL as opposed to verbal-spatial polarity coding. Better arithmetic performances due to more efficient procedural calculations might hardly strengthen the association of numerical magnitudes with verbal labels, especially when considering that the latter cognitive processes in turn rather detrimentally affect arithmetic problem solving. However, since verbal-spatial coding mechanisms probably only emerge at later developmental stages (Imbo et al., 2012; Pickering, 2011; van Galen & Reitsma, 2008), the parity SNARC effect likely predominantly resulted from the MNL in the relatively younger children, such that a reverse relation where arithmetical abilities strengthen spatial-numerical mappings on the MNL is certainly possible at that age. The gradual age-related shift towards fact retrieval during arithmetic problem solving might then again account for the lack of correlation between the parity SNARC effect and arithmetical abilities in the relatively older children, if we assume that simply retrieving facts from long-term memory does not activate and as such alter any basic numerical magnitude representations. This assumption is supported by studies showing that fact retrieval mainly relies on the activation of brain areas in the angular gyrus (Grabner et al., 2009), while the SNARC effect is thought to have its locus in the IPS (Cutini et al., 2014; Rusconi et al., 2007, 2013). Moreover, when further pursuing the idea of a feedback loop, strengthening basic numerical representations at later developmental stages might be rather redundant, considering that individuals predominantly rely on fact retrieval during math problem solving not engaging these numerical representations.

A reverse relation is also certainly possible in *study 2* in that greater math anxiety leads to stronger parity SNARC effects. Math anxiety could for instance reduce math practice (see global avoidance theory by Ashcraft & Faust, 1994). Insufficient math training might then require individuals to rely on less sophisticated procedural calculations during math problem solving (De Smedt et al., 2011; Grabner et al., 2007; Lemaire, 2010), potentially involving the activation of numerical magnitudes either on a spatially oriented MNL or within a spatial sequence temporarily stored in WM. Greater reliance on such suboptimal strategies and the spatial codes associated with numerical magnitudes in arithmetic tasks might then not only negatively affect math performances, but also alter/strengthen spatial-numerical mappings either on the MNL or within WM, manifesting in stronger parity SNARC effects. Nonetheless, although such practice-mediated alterations in spatial-numerical mappings are certainly possible at earlier development stages (e.g., Mussolin et al., 2014; Patro, Fischer et al., 2016), it is slightly less clear whether basic numerical representations (especially on a long-term MNL) are still malleable in adulthood and as such can be modified. In addition, the lack of correlation between arithmetic performances and the distance effect suggests that individuals unlikely relied on procedural calculations involving the MNL during math problem solving (but see van Opstal et al., 2008, for an alternative explanation of the distance effect). Greater reliance on suboptimal MNL-based calculations in arithmetic tasks might thus not account for the stronger parity SNARC effects in individuals with greater math anxiety. Moreover, considering that the parity SNARC effect most likely resulted from verbal-spatial polarity coding at the population level (see also study 3), a more likely alternative explanation for a reverse relation might be as follows: greater math anxiety and the associated higher susceptibility to distraction (see deficient attentional control theory by Eysenck et al., 2007; Eysenck & Calvo, 1992; Hopko et al., 1998) might facilitate the association of numerical magnitudes with irrelevant verbal codes during numerical tasks, manifesting in stronger parity SNARC effects. The greater vulnerability to distraction in high math anxious individuals could also enhance the irrelevant activation of numerical magnitudes either on a spatially oriented MNL or within a spatial sequence temporarily stored in WM during parity judgments, consequently explaining the stronger parity SNARC effects also in those (few) individuals activating visuospatial (as opposed to verbal-spatial) coding mechanisms.

To resolve such causality issues, one might for instance design intervention studies in which arithmetical abilities are trained. The absence of any transfer effects to the strength of the parity SNARC effect would then rule out a reverse relation. Arithmetic training should, however, be abstract and not comprise any spatial aspects to exclude the possibility that the spatial coding mechanisms underlying the parity SNARC effect are also strengthened by the training paradigm. Embodied trainings might thus not be suited for this purpose (e.g., Fischer et al., 2011; Link et al., 2013). Moreover, the training needs to specifically ameliorate procedural calculations rather than fact retrieval, since the latter strategy is unlikely related to the parity SNARC effect anyway. This might, however, be quite challenging, considering that arithmetic training often leads to a shift towards greater reliance on fact retrieval (e.g., Imbo & Vandierendonck, 2008). With regard to math anxiety, one could develop studies in which this affective variable is either relieved (e.g., through expressive writing, see Park, Ramirez, & Beilock, 2014) or experimentally induced (e.g., by exposing women to a stereotyping message regarding better math performances in men) and subsequently measure transfer effects to the size of the parity SNARC effect.

Apart from the causality issue, studies 1 and 2 did also not consider the potential influence of ***confounders*** in the relations between the parity SNARC effect and either arithmetical abilities or math anxiety.

In *study 1*, the relation between stronger parity SNARC effects and better arithmetical abilities in the relatively younger children might for instance be confounded by WM capacity, if we assume that the parity SNARC effect resulted from the WM account. Namely, greater WM might not only facilitate the spatial storage of numerical magnitudes in their canonical order in WM, causing stronger parity SNARC effects (Georges, Hoffmann, & Schiltz, 2013), but also relate to better math performances (e.g., Bull & Scerif, 2001; DeStefano & LeFevre, 2004; Raghubar et al., 2010), especially in younger children using procedural calculations to solve arithmetic problems (Geary et al., 2004; Peng et al., 2016; Siegler, 1998). Less reliance on WM-based strategies in arithmetic tasks at later developmental stages might then also explain the lack of correlation between the parity SNARC effect and arithmetical abilities in the relatively older children. The potential involvement of WM in the relation between the parity SNARC effect and arithmetical abilities should thus be investigated in future studies.

In *study 2*, the relation between stronger parity SNARC effects and greater math anxiety might also be confounded by extraneous variables. One such confounder might be math training, which could for instance depend on school curricula or work activities rather than on math anxiety (see global avoidance theory by Ashcraft & Faust, 1994). Insufficient math training and the associated greater reliance on less efficient procedural calculations, potentially involving the activation of numerical magnitudes either on a spatially oriented MNL or within a spatial sequence temporarily stored in WM, during math problem solving would then not only alter/strengthen these underlying spatial coding processes (manifesting in stronger parity SNARC effects), but also negatively affect math performances (e.g., Grabner et al., 2007), thereby leading to the emergence of math anxiety.

Another potential confounder might be inhibitory control, which could for instance depend on innate traits such as attention-deficit/hyperactivity disorder (Schachar, Tannock, Marriott, & Logan, 1995) rather than on math anxiety, affecting the balance between top-down and bottom-up attentional processes (see deficient attentional control theory by Eysenck et al., 2007; Eysenck & Calvo, 1992; Hopko et al., 1998). The greater susceptibility to distraction associated with weaker inhibitory control would then not only strengthen the parity SNARC effect via facilitating the association of numerical magnitudes with irrelevant verbal/visuospatial codes during parity judgments (see also Hoffmann, Pigat et al., 2014), but also negatively affect math performances (Bull & Scerif, 2001; Cragg & Gilmore, 2014), thereby leading to the emergence of math anxiety. In this framework, inhibitory control affects math skills independently of its influences on the parity SNARC effect. This thus differs from the aforementioned hypothesis that lower inhibitory control might cause weaker math skills via strengthening irrelevant verbal/visuospatial coding of numerical magnitudes in number processing tasks (i.e., the parity SNARC effect). Nonetheless, the assumption that inhibitory control might be a confounder in the relation between the parity SNARC effect and math anxiety seems rather unlikely, since the parity SNARC effect explained variance in math anxiety even after controlling for general inhibition capacities.

A final potential confounder could be math abilities. Math learning difficulties due to a developmental math disorder, such as dyscalculia, might not only lead to the emergence of math anxiety (Rubinsten & Tannock, 2010), but also relate to altered numerical magnitude representations (e.g., Mazzocco et al., 2011; see also Price & Ansari, 2013), potentially manifesting in stronger parity SNARC effects (Hoffmann, Mussolin et al., 2014). However, since the parity SNARC effect predicted math anxiety even after partialling out the influence of arithmetic performances, math abilities are hardly a confounder in the relation between stronger parity SNARC effects and greater math anxiety.

Another challenge for future research is to investigate the relations between the ***magnitude SNARC effect*** and arithmetical abilities as well as math anxiety. Since the parity and magnitude SNARC effects did not correlate and also differentially related to arithmetic performances and visualization profile respectively at the population level in adults (see study 3), the SNARC effect in implicit and explicit tasks likely arises from different spatial coding processes in most adults. Consequently, different outcomes can be expected with the magnitude than the parity SNARC effect (at least at the population level). Contrasting the results observed with both SNARC effects could then provide valuable information regarding not only the spatial coding processes underlying these effects, but also the cognitive mechanisms actually contributing to arithmetical abilities as well as math anxiety.

Nonetheless, the task-dependency of the spatial coding mechanisms underlying the SNARC effect in adults might not apply to children. Especially in younger individuals, the parity and magnitude SNARC effects might both predominantly arise from visuospatial coding mechanisms involving either the MNL or WM. This assumption is based on the observation that the magnitude SNARC effect likely resulted from such visuospatial coding processes also at later developmental stages in adults (see study 3). In addition, the verbal-spatial account, which could potentially underlie the parity SNARC effect in the majority of adults (see study 3), probably only emerges later in life (Imbo et al., 2012; Pickering, 2001; van Galen & Reitsma, 2008). Consequently, similar outcomes might be obtained regardless of whether the SNARC effect is assessed in the implicit or explicit number processing task at earlier developmental stages.

In *study 1*, stronger magnitude SNARC effects might thus also relate to better arithmetical skills in the relatively younger children, similarly to the parity SNARC effect. Conversely, in older children, the SNARC effects in implicit and explicit tasks might differentially associate with arithmetical abilities due to the gradual age-related shift towards verbal-spatial polarity coding only during parity judgments but not magnitude classifications in most individuals (see study 3). Since the magnitude SNARC effect was not associated with arithmetic performances in adults (see study 3), it might also not relate to arithmetical skills in the relatively older children, but for reasons other than those explaining the null relation between the parity SNARC effect and arithmetical abilities at these later developmental stages.

In *study 2*, the magnitude SNARC effect might not associate with math anxiety, since it was not related to arithmetic performances in the majority of adults (see study 3). This assumption is, however, only valid if we assume that math skills actually mediate the relation between the SNARC effect and math anxiety. Even though the associations of math anxiety with the parity and magnitude SNARC effects might differ like so at the population level, such differential relations might not be observed in individuals relying on a single spatial coding account regardless of the implicit or explicit nature of the number processing task (e.g., object- and spatial-visualizers). More concretely, greater math anxiety might be associated with stronger SNARC effects also in the magnitude classification task, especially in those individuals predominantly activating verbal-spatial coding processes in both implicit and explicit tasks. This idea is based on the observations that the parity SNARC effect probably resulted from such verbal-spatial polarity coding in most adults (see study 3) and was also related to math anxiety at the population level (see study 2). As such, the relation between the magnitude SNARC effect and math skills/anxiety might be moderated by the cognitive variables also determining the spatial nature of its underlying coding processes (i.e., visualization profile and arithmetic performances; see study 3). Observing a relation between the magnitude SNARC effect and math anxiety only in those individuals relying on verbal-spatial polarity coding would provide evidence in favor of the assumption that the association of numerical magnitudes with irrelevant verbal codes mainly accounts for the relation between stronger parity SNARC effects and weaker math skills/greater math anxiety. Such irrelevant verbal coding in numerical tasks possibly results from weaker inhibitory control. However, since numerical magnitude processing is essential in the magnitude classification task and since the activation of the magnitude-associated verbal (or visuospatial) codes probably even supports successful task completion in the latter instance, this inhibitory problem might not be revealed by assessing the magnitude SNARC effect. This could then also account for the lack of correlation between the magnitude SNARC effect and math performances (see study 3), irrespective of the spatial coding account underlying this effect, if we assume that inhibition capacities actually contribute to the relation between the parity SNARC effect and math abilities. Consequently, the absence of a relation between the magnitude SNARC effect and math anxiety even in individuals favouring verbal-spatial polarity coding would strengthen the idea that the relation between stronger parity SNARC effects and weaker math skills/greater math anxiety is explained by the inability to efficiently inhibit the irrelevant verbal/visuospatial codes associated with numerical magnitudes during the completion of arithmetic tasks.

Finally, assessing the relation between the magnitude SNARC effect and math anxiety in adults might not advance our understanding of the cognitive processes actually involved in the *emergence* of math anxiety, since the spatial coding mechanisms underlying this effect and their relation to math skills might change from the time math anxiety emerges until adulthood. The relation between the magnitude SNARC effect and math anxiety should thus also be assessed at the time math anxiety arises in 6-year-olds (Krinzinger et al., 2009).

9.3 General Summary and Conclusion

This thesis pursued two different yet related research goals. Firstly, we were interested in whether number-space associations, as indexed by the parity SNARC effect, relate to mathematical abilities in elementary school children as well as math anxiety in adults. Secondly, we aimed to determine the spatial nature of the coding mechanisms underlying number-space associations, such as the SNARC effect, in different contexts and individuals to get a more complete picture of the specific cognitive processes potentially contributing to mathematical development. A better understanding of the neural mechanisms accounting for the strong connection between numerical and spatial concepts and of how these processes relate to mathematical competencies will not only help create improved diagnostics to screen for individuals at risk of developing math learning difficulties and/or anxiety, but will also enable the design of appropriate interventions to foster math abilities in both typically and atypically developing individuals.

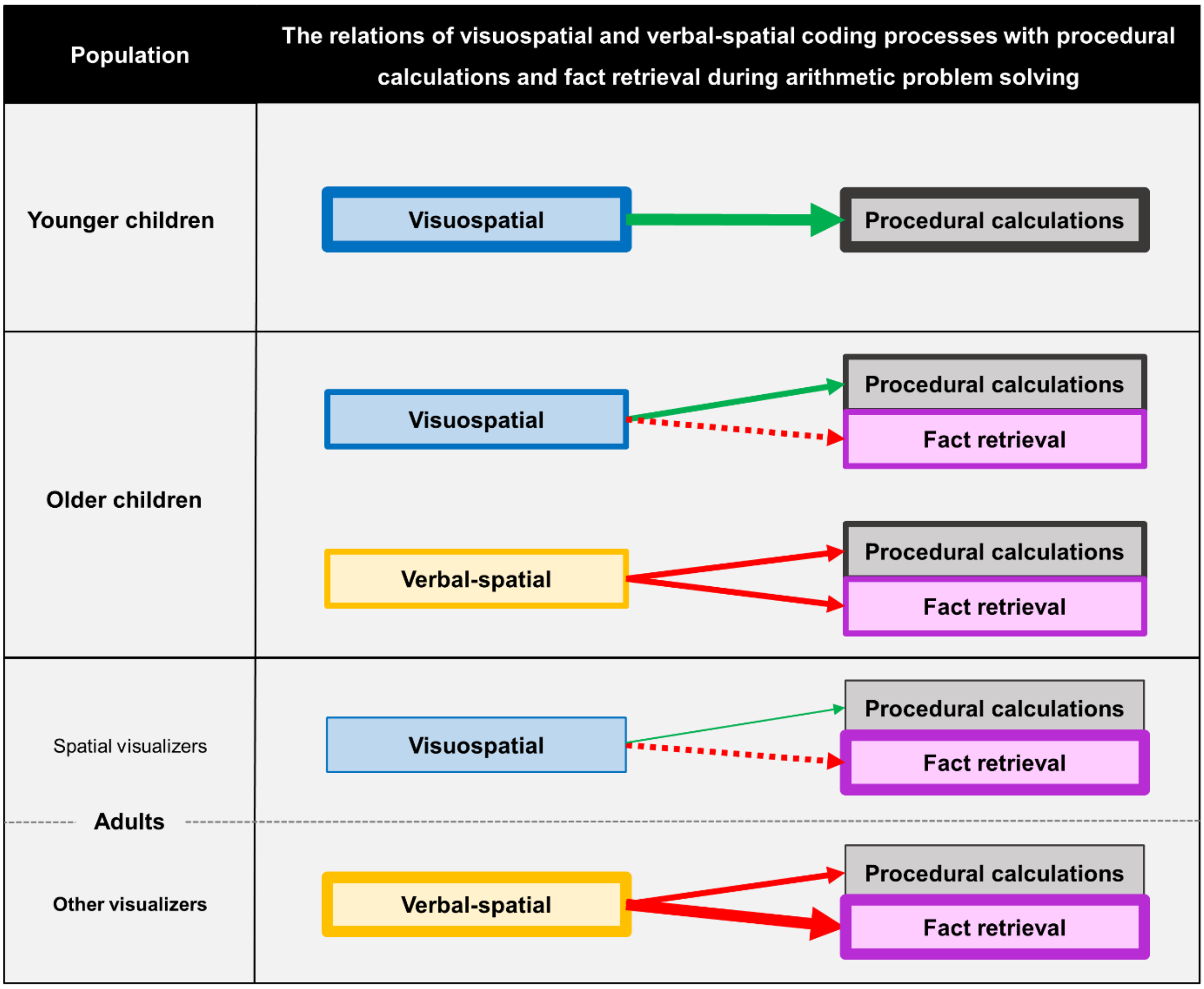
Contrary to some believes (e.g., Cheung et al., 2015; Gevers et al., 2010), the spatial coding mechanisms underlying the SNARC effect in adults varied intra-individually depending on contextual factors such as the implicit or explicit nature of the number processing task and the task instructions. Moreover, the extent of this intra-individual variance was conditional upon inter-individual differences in cognitive factors including visualization profile and arithmetic performances. These findings thus complement previous studies, reporting that the SNARC effect in the parity judgement and magnitude classification tasks resulted from different spatial coding processes at the population level (van Dijck et al., 2009, 2012). They also extent this task-dependency by showing for the first time that task instructions also play a role in determining the spatial nature of the coding mechanisms underlying the SNARC effect in the explicit magnitude classification task. Moreover, we are the first to reveal that the context-dependency of the spatial coding accounts explaining the SNARC effect depends on inter-individual differences in cognitive variables. Individuals with clear preferences for either object or spatial visualizations likely activated a single predominant (or at least related) spatial coding mechanism(s) regardless of the implicit or explicit nature of the task. Nonetheless, since positive and negative correlations between the parity and magnitude SNARC effects were observed in object- and spatial-visualizers respectively, the spatial nature of these coding processes probably varied between the latter types of individuals. While spatial-visualizers most likely exclusively relied on visuospatial coding processes, the SNARC effect probably predominantly resulted from verbal-spatial polarity coding in object-visualizers (see Schema 1). Conversely, multiple task-dependent spatial coding accounts were activated in mixed-visualizers, with visuospatial and verbal-spatial coding mechanisms possibly contributing to their magnitude and parity SNARC effects respectively. Individual characteristics thus not only determine the strength of the SNARC effect (e.g., Hoffmann, Mussolin et al., 2014; Hoffmann, Pigat et al., 2014; Viarouge et al., 2014), but also its underlying spatial coding processes. Altogether, this could potentially explain some of the previously reported inconsistencies in the literature regarding the predominance as well as the specific spatial nature of the coding mechanisms underlying number-space associations, such as the SNARC effect (see e.g., Cheung et al., 2015; Gevers et al., 2010, for the predominance of a single spatial coding account versus Müller & Schwarz, 2007; Priftis et al., 2006; van Dijck et al., 2009, 2012, for task-dependent spatial coding mechanisms).

The spatial coding mechanisms underlying the parity SNARC effect also related to mathematics. Namely, stronger parity SNARC effects were associated with better arithmetical (but not visuospatial) math abilities in the relatively younger third to fourth grade elementary school children. Procedural calculations relying on visuospatial coding processes based on the activation of numerical magnitudes either on a long-term spatially oriented MNL or within a spatial sequence temporarily stored in WM are thus probably involved in successful arithmetic problem solving at relatively earlier stages of math development (see Schema 1). Since the positive relation between stronger parity SNARC effects and better arithmetic skills can be less easily reconciled with the verbal-spatial coding account, the latter coding processes likely only emerge later in life. This assumption agrees with studies reporting that the ability to rely on the phonological system to verbally recode visually presented information only arises at about 8 years of age (Pickering, 2001). A potential shift towards verbal-spatial polarity coding at later developmental stages (in some or even most children) as well as an age-related strategic change from procedural calculations involving either the MNL or WM towards fact retrieval from long-term memory during arithmetic problem solving (in the majority of individuals) might then account for the lack of correlation between the parity SNARC effect and arithmetical abilities in the relatively older children at the population level. At later developmental stages, positive associations between stronger parity SNARC effects and better arithmetic skills might further be observed in those children relying on visuospatial coding mechanisms based on either the MNL or WM during numerical processing and still adopting procedural calculation strategies involving the MNL or WM to solve arithmetic problems. However, it should be mentioned here that even though stronger visuospatial coding in numerical tasks (i.e., stronger parity SNARC effects) might assist procedural calculations, this could at some point negatively relate to arithmetic performances, as relying on such procedural calculation strategies during arithmetic problem solving is usually considered inferior to resorting to fact retrieval (Berteletti et al., 2014; De Smedt, Holloway, & Ansari, 2011). Since retrieving facts from long-term memory does not depend (or to a lesser extent) on the spatial representation of numerical magnitudes on the MNL or within WM, the extent of visuospatial coding involving the MNL or WM in numerical tasks (i.e., the parity SNARC effect) might not relate to arithmetic performances in children relying on fact retrieval to solve arithmetic problems. Considering the irrelevance of such spatial-numerical mappings on the MNL or within WM for efficient fact retrieval, the former might even negatively associate with arithmetic skills due to their interference with optimal fact retrieval. Such negative relations between stronger parity SNARC effects and weaker arithmetical abilities might also be evidenced in children predominantly activating verbal-spatial polarity coding in numerical tasks independently of whether arithmetic problem solving relies on procedural calculations or fact retrieval (see Schema 1). Altogether, these findings not only advance our understanding of the cognitive processes important for successful arithmetic problem solving at different developmental stages, but also provide further information with regard to the spatial coding mechanisms potentially underlying the parity SNARC effect in children. In addition, the present results suggest that embodied training paradigms focussing on strengthening number-space mappings might be most beneficial for enhancing arithmetic skills in relatively younger children prior to grade 4.

Interestingly, the spatial coding mechanisms underlying the parity SNARC effect also related to math anxiety in adults. Namely, stronger parity SNARC effects were associated with greater math anxiety. Since the parity SNARC effect did not correlate with visualization profile, was unrelated to the distance effect and associated with weaker rather than stronger WM at the population level, it probably resulted from verbal-spatial coding processes in the majority of adults (see Schema 1). Consequently, such verbal-spatial polarity coding in numerical tasks might explain the relation between stronger parity SNARC effects and greater math anxiety. Accordingly, stronger associations of numerical magnitudes with verbal codes during number processing might not only manifest in more pronounced parity SNARC effects, but also interfere with efficient strategy use (probably fact retrieval) in arithmetic tasks. This could then negatively affect math performances, ultimately leading to the development of math anxiety. Especially individuals with weaker inhibition capacities might fail to inhibit such irrelevant verbal coding in numerical tasks (Hoffmann, Pigat et al., 2014) and in turn suffer from the negative consequences (i.e., weaker math skills/greater math anxiety). This idea thus stresses the critical involvement of inhibitory control processes in the relation between stronger parity SNARC effects and the weaker math skills ultimately leading to greater math anxiety. Consequently, this affective variable might not only disrupt inhibition processes, as it is suggested in the deficient attentional control theory (Eysenck et al., 2007; extension of the processing efficiency theory proposed by Eysenck & Calvo, 1992; see also Hopko et al., 1998), but also result from inhibitory deficits. In particular the inability to efficiently suppress irrelevant (probably verbal) coding of numerical magnitudes in numerical tasks might cause the math difficulties associated with greater math anxiety. This assumption is based on the finding that the parity SNARC effect predicted math anxiety even after controlling for general inhibition capacities. Nonetheless, the idea that math anxiety results from a specific deficit to inhibit irrelevant verbal codes during math problem solving needs further investigation. Moreover, the relation between the parity SNARC effect and math anxiety should be tested at the time this affective disorder first arises to get a better idea of whether number-space associations actually represent a risk factor for the emergence of math anxiety or merely affect this affective variable throughout life.

In general, the association of numerical magnitudes with multiple different spatial codes that are likely both visuospatial and verbal-spatial in nature and probably established both at a long-term level and temporarily within WM (Ginsburg & Gevers, 2015; Huber et al., 2016) further highlights the robustness of the connection between numerical and spatial representations, probably constituting an innate trait of human cognition. Furthermore, the relation of the spatial coding mechanisms underlying the parity SNARC effect with both cognitive and affective factors of mathematics stresses the crucial importance of such basic spatial-numerical mappings for adequate mathematical development. Nonetheless, whether the interaction between numerical and spatial concepts beneficially or rather detrimentally contributes to mathematical learning seems to depend on the visuospatial and verbal-spatial nature of the codes associated with numerical magnitudes. Since the association of numerical quantities with visuospatial codes on the MNL or within WM seems to positively affect arithmetic problem solving (at least earlier in life), spatial-numerical associations might support mathematical learning in individuals relying on such visuospatial coding processes. Conversely, since verbal polarity coding might be rather detrimental for math performances and as such even contribute to math anxiety, especially if the verbal codes cannot be efficiently suppressed, individuals associating numerical magnitudes with such verbal(-spatial) codes might be hindered in their adequate mathematical development. Relying on spatial aspects in numerical tasks might thus be a valuable tool potentially promoting the acquisition of math skills, but only in those individuals that know how to use such spatial-numerical coding to their advantage during math problem solving.

Finally, it should be noted that we focussed on the SNARC effect as an index of number-space associations. Nonetheless, as stated by Fischer and Shaki (2014), the SNARC effect specifically reflects the numerical magnitude-related spatial bias in speeded choices between two alternative responses, while the spatial bias observed in other numerical tasks, such as for instance during random number generations, might occur independently of laterized choices or time constraints. As such, the present findings with the SNARC effect might not be generalizable to all types of number-space associations. Future studies should thus determine whether the spatial coding mechanisms underlying the spatial bias evidenced in other numerical tasks also depend on contextual factors. In the random number generation task, different spatial coding processes could for instance be activated depending on whether numbers are generated following head movements (Loetscher et al., 2008) or full body turns (Shaki & Fischer, 2014). Consequently, even though this thesis advances our understanding of the spatial coding mechanisms underlying number-space associations, such as the SNARC effect, and also of how these cognitive processes contribute to mathematical development, the present research has only touched the tip of the iceberg and further investigations are needed to thoroughly understand the connections between numerical and spatial concepts and their importance for mathematical learning.



Schema 1. The potential relations of the visuospatial and verbal-spatial coding processes underlying the parity SNARC effect with the procedural calculation and fact retrieval strategies adopted during arithmetic problem solving at the different developmental stages. Positive and negative associations are highlighted in green and red respectively. A potential negative relation is indicated by a red dotted arrow. The relative contributions of the different spatial coding processes and strategies to the parity SNARC effect and arithmetic problem solving respectively in the different populations are reflected by the weights of the outlines, with stronger weights indicating greater contributions. Especially spatial-visualizers might activate visuospatial coding processes even in adulthood. All other adults might predominantly rely on verbal-spatial coding processes.

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