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

PsychOpen publishing psychology

Research Reports

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

Carrie Georges*[a], Danielle Hoffmann[b], Christine Schiltz[a]

[a] Institute of Cognitive Science and Assessment (COSA), Research Unit Education, Culture, Cognition and Society (ECCS), Faculty of Language and Literature, Humanities, Arts and Education (FLSHASE), University of Luxembourg, Luxembourg. **[b]** Centre for Educational Testing (LUCET), Faculty of Language and Literature, Humanities, Arts and Education (FLSHASE), University of Luxembourg, Luxembourg.

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

Journal of Numerical Cognition, 2017, Vol. 3(2), 182–211, doi:10.5964/jnc.v3i2.46

Received: 2016-05-13. Accepted: 2017-03-02. Published (VoR): 2017-12-22.

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

*Corresponding author at: Institute of Cognitive Science and Assessment (COSA), Research Unit Education, Culture, Cognition and Society (ECCS), Faculty of Language and Literature, Humanities, Arts and Education (FLSHASE), University of Luxembourg, Campus Belval, Maison des Sciences Humaines, 11, Porte des Sciences, L-4366 Esch-sur-Alzette, Luxembourg. E-mail: carrie.georges@uni.lu

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.

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, Schwarz, Schubiger, & Brugger, 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 (Herrera, 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 et al., 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 parity SNAs 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). 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 show 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 vs. 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 vs. 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 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.

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 SNAs 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, et al., 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, Mussolin, et al., 2014), while the weakest parity SNAs were evidenced in math professionals (Cipora et al., 2016). In addition to this, 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 SNAs (Viarouge et al., 2014).

Interestingly, however, despite these findings associating individual differences in arithmetic and spatial skills with variability in the parity SNAs, 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.

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 SNAs 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 SNAs 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 SNAs 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 SNAs, 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 regards 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.

Methods

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

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.

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.

The present study was conducted in the context of a larger project, assessing amongst others the relation between number-space associations and math anxiety. The latter research findings have recently been published elsewhere (see Georges, Hoffmann, & Schiltz, 2016). Considering that the current investigation was part of a broader 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).

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 ($F(1, 80) = 13.95$, $p < .001$, $\eta_p^2 = .15$). 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, $F(1, 80) = .27$, $p = .61$, $\eta_p^2 = .003$).

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, Iversen, & Willmes, 2004) might negatively affect the overall fit of dRTs to the regression line, especially in the parity judgment task[i]. 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 vs. 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 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: $r = .38$ vs. 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 Appendix.

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 (Nunnally, 1978).

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 half, a short break, and then four minutes to complete the second half.

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).

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.

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 focussed 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 variables 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.

Results

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 ($F(1, 80) = 7.14$, $p < .01$, $\eta_p^2 = .08$), 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* ($F(1, 80) = 3.97$, $p = .05$, $\eta_p^2 = .05$), 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 Appendix.

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.

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

Cognitive variables	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* = .07. **p* < .05 (non-significant when adjusting for multiple comparisons using Holm-Bonferroni).

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.

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.

Regression analyses thus suggest that SNAs in implicit and explicit tasks rely on different cognitive mechanisms. However, at this point, we also have to consider the non-perfect reliabilities of some of the variables included in the regression models (notably 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). Consequently, low reliabilities, especially in the parity judgment task, might also account for the absence of a significant relation between the different SNAs and/or explain the differential relations of the parity and magnitude SNAs with the different numerical and spatial factors in this study.

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	.20
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, $F(4, 76) = 2.06$, $p = .09$.

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 ($\Delta R^2 = .07$, $b = -0.05$, $t(77) = -2.46$, $p = .02$, 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.

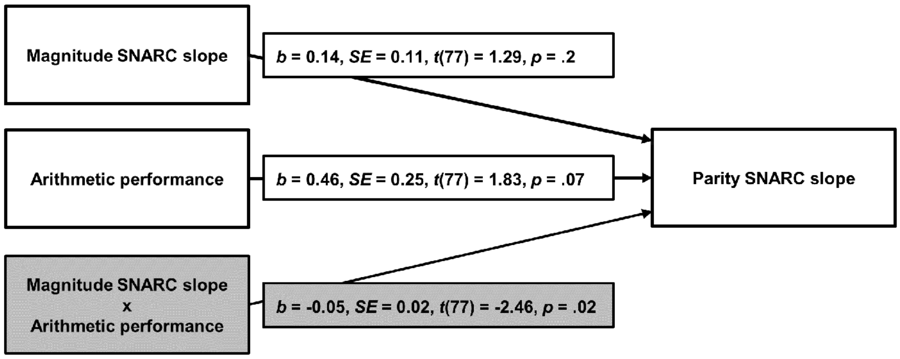

Figure 1. Simple moderation analysis results for arithmetic performance with unstandardized regression coefficients.

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).

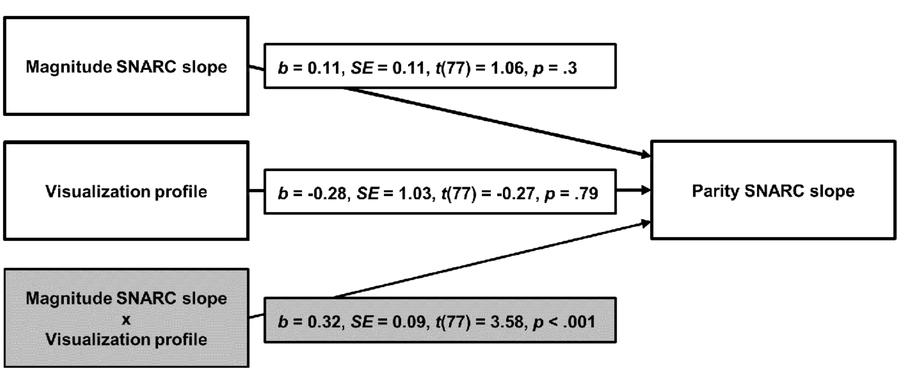

Figure 2. Simple moderation analysis results for visualization profile with unstandardized regression coefficients.

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).

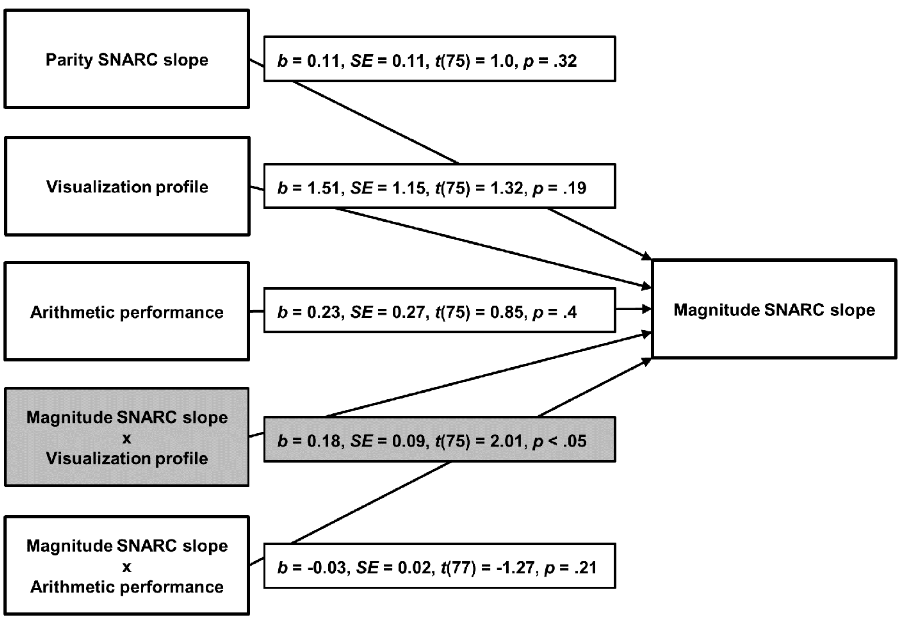

Figure 3. Multiple additive moderation analysis results with unstandardized regression coefficients.

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.

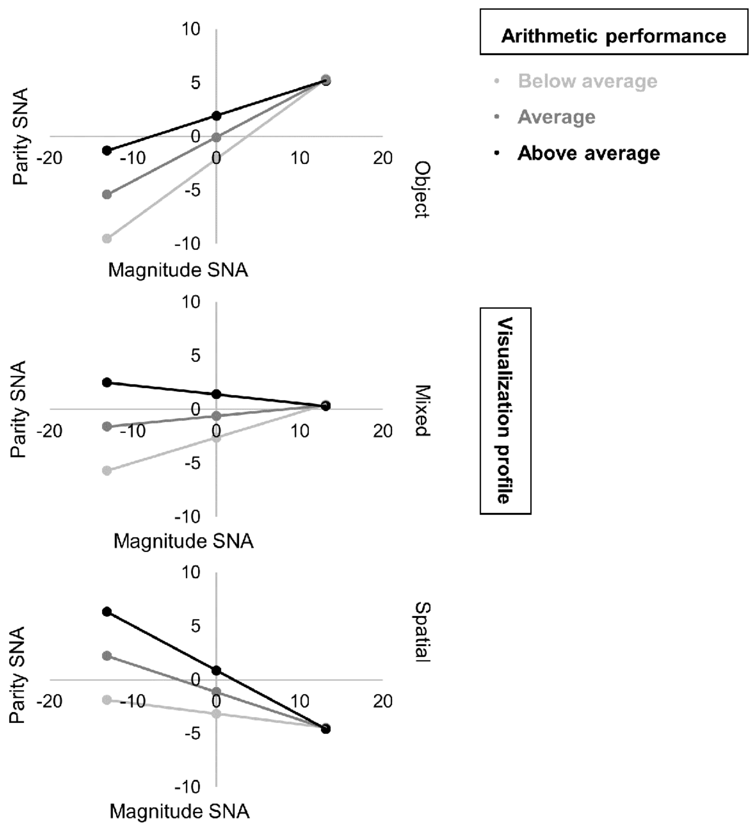

Figure 4. The relationship between parity and magnitude SNARC regression slopes at the means and at one standard deviation below and above the means of arithmetic performance and visualization profile.

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 parity and magnitude SNAs 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.

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, which is in line with the positive association between SNAs in implicit and explicit tasks recently reported by Cheung et al. (2015). This outcome thus suggests 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 would nicely complement previous findings regarding the predominance of a single (verbal) spatial coding account regardless of the nature of the numerical task (e.g., Gevers et al., 2010).

On the other hand, the present results also showed that SNAs in the parity judgment and magnitude classification tasks were correlated with and predicted by different cognitive variables, namely arithmetic performance and visualization profile respectively. In addition, 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. Those findings thus rather suggest that number-space associations in tasks with implicit and explicit magnitude processing arise from at least partially unrelated spatial coding mechanisms. This outcome would be 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. It would 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 would fit nicely with the context dependency of number-space associations recently reported by Georges et al. (2015), where the spatial nature of the cognitive processes underlying number-space associations depended on task instructions.

Although interesting per se, the aforementioned correlation and regression analyses outcomes seem fairly inconclusive and provide somehow conflicting results with regard to whether number-space associations in implicit and explicit tasks result from a single predominant or multiple task-dependent spatial coding mechanism(s). On the one hand, a tendency for a correlation was revealed between the parity and magnitude SNAs, suggesting the activation of a single spatial coding process. Conversely, these two variables were each associated with different cognitive factors, thereby rather indicating task-dependent spatial coding mechanisms. One explanation for this discrepancy might be the non-perfect reliabilities of some of the variables included in this study, especially of the parity SNARC regression slopes. Low reliability usually results in the underestimation of bivariate correlations, consequently increasing the risk of type II errors. Moreover, it potentially biases unstandardized coefficients and/or leads to erroneous statistical significance levels in regression analysis (Osborne & Waters, 2002). As such, the significantly lower split-half reliability in the parity judgment compared to the magnitude classification task could have been responsible for the differential relations of the parity and magnitude SNAs with the numerical and spatial factors in this study. Since divergent reliabilities might provide an alternative explanation for the differential associations of implicit and explicit SNAs with the diverse cognitive variables in this study, we need to be careful before drawing conclusions about task-dependent spatial coding mechanisms solely based on the present correlation and regression analyses outcomes.

PsychOpen
publishing psychology

Considering that the aforementioned analyses did not allow us to fully resolve inconsistencies in the literature regarding the cognitive origins of number-space associations, we finally performed moderation analyses to determine whether the relation between SNAs 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 number-space associations (namely arithmetic performance and visualization profile). Interestingly, the relation between the two SNAs was indeed moderated by visualization profile and arithmetic performance. This outcome thus sheds 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.

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 SNAs 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, Mussolin, 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 thus 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, relations between the parity SNARC regression slopes and the cognitive variables in this study need to be interpreted with caution, given the relatively low reliability of the parity SNAs. Consequently, the involvement of visuospatial processing resources in the emergence of parity SNAs should 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., 2008). 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 SNAs. 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 SNAs and arithmetic performance (see Cipora et al., 2016 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 magnitude SNAs 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.

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 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 3-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 regards 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 also need to bear in mind the non-perfect reliabilities of some of the variables included in this study, especially of the parity SNARC regression slopes. The relatively low reliability of this variable could for instance be explained by the small number of repetitions per digit for each response side (i.e., 9 repetitions), since a considerably 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). Nonetheless, a shorter task length cannot account for the significant difference in reliabilities between the parity judgment and magnitude classification tasks, since both tasks were equally short. Considering the effects of unreliable measurements on correlation and regression analyses outcomes (Osborne & Waters, 2002), the relatively poor reliability of the parity SNARC regression slopes could have caused the absence of significant association between implicit and explicit SNAs. Moreover, the significantly lower split-half reliability in the parity judgment compared to the magnitude classification task might have been responsible for the differential relations of the parity and magnitude SNAs with the different numerical and spatial factors in this study (notably visualization profile). We thus need to be careful before drawing conclusions about task-dependent spatial coding mechanisms with a specific contribution of visuospatial coding mechanisms only to explicit SNAs (at the population level) solely based on the present correlation and regression analyses outcomes. Even though moderation analyses enabled us to shed further light onto the mechanisms actually underlying number-space associations in implicit and explicit tasks, the present investigation should ideally be repeated with longer tasks (i.e., 20 instead of 9 repetitions per stimulus for each response side, see Cipora & Nuerk, 2013; Cipora & Wood, 2012; Cipora et al., 2016) and consequently more reliable measurements.

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 regards 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 physical 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.

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 associations between the parity and magnitude SNAs were observed in object-visualizers with lower arithmetic performance and spatial-visualizers with higher arithmetic performance 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, suggesting the contribution of visuospatial coding mechanisms only to number-space associations in explicit but not implicit tasks (at least at the population level). Ideally, these results should, however, be confirmed by future studies with longer testing sessions allowing to obtain more reliable measurements.

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.

Notes

i) 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, η_p^2 = .04, odd dRT = 10.46 ms, even dRT = -19.9 ms), but not the magnitude classification task (F = .01, p = .92, η_p^2 = .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. The presence of a MARC effect only in the parity judgment task is clearly in line with predictions regarding this effect (Nuerk et al., 2004; Nuerk, Wood, & Willmes, 2005).

Funding

This work was supported by the National Research Fund Luxembourg (FNR; www.fnr.lu) under Grant AFR PHD-2012-2/4641711.

Competing Interests

It is certified that there is no conflict of interest with any financial organization regarding the material discussed in the manuscript.

Acknowledgments

The authors have no support to report.

References

Anderson, K. L., Casey, M. B., Thompson, W. L., Burrage, M. S., Perazis, E., & Kosslyn, S. M. (2008). Performance on middle school geometry problems with geometry clues matched to three different cognitive styles. *Mind, Brain and Education, 2*(4), 188-197. doi:10.1111/j.1751-228X.2008.00053.x

Bächtold, D., Baumüller, M., & Brugger, P. (1998). Stimulus–response compatibility in representational space. *Neuropsychologia, 36*, 731-735. doi:10.1016/S0028-3932(98)00002-5

Berch, D. B., Foley, E. J., Hill, R. J., & Ryan, P. M. (1999). Extracting parity and magnitude from Arabic numerals: Developmental changes in number processing and mental representation. *Journal of Experimental Child Psychology, 74*, 286-308. doi:10.1006/jecp.1999.2518

Blajenkova, O., Kozhevnikov, M., & Motes, M. A. (2006). Object–spatial imagery: A new self-report imagery questionnaire. *Applied Cognitive Psychology, 20*, 239-263. doi:10.1002/acp.1182

Blazhenkova, O., Becker, M., & Kozhevnikov, M. (2011). Object-spatial imagery and verbal cognitive styles in children and adolescents: Developmental trajectories in relation to ability. *Learning and Individual Differences, 21*, 281-287. doi:10.1016/j.lindif.2010.11.012

Bull, R., Marschark, M., & Blatto-Valle, G. (2005). SNARC hunting: Examining number representation in deaf students. *Learning and Individual Differences, 15*, 223-236. doi:10.1016/j.lindif.2005.01.004

Caissie, A. F., Vigneau, F., & Bors, D. A. (2009). What does the Mental Rotation Test measure? An analysis of item difficulty and item characteristics. *The Open Psychology Journal, 2*, 94-102. doi:10.2174/1874350100902010094

Carlson, S. M., & Moses, L. J. (2001). Individual differences in inhibitory control and children's theory of mind. *Child Development, 72*, 1032-1053. doi:10.1111/1467-8624.00333

Cheung, C.-N., Ayzenberg, V., Diamond, R. F., Yousif, S., & Lourenco, S. F. (2015). Probing the mental number line: A between-task analysis of spatial-numerical associations. In D. C. Noelle, R. Dale, A. S. Warlaumont, J. Yoshimi, T. Matlock, C. D. Jennings, & P. P. Maglio (Eds.), *Proceedings of the 37th Annual Meeting of the Cognitive Science Society* (pp. 357-362). Austin, TX, USA: Cognitive Science Society.

Chrysostomou, M., Pitta-Pantazi, D., Tsingi, C., Cleanthous, E., & Christou, C. (2013). Cognitive styles and their relation to number sense and algebraic reasoning. *Educational Studies in Mathematics, 83*(2), 205-223. doi:10.1007/s10649-012-9448-0

Cipora, K., Hohol, M., Nuerk, H.-C., Willmes, K., Brożek, B., Kucharzyk, B., & Nęcka, E. (2016). Professional mathematicians differ from controls in their spatial-numerical associations. *Psychological Research, 80*, 710-726. doi:10.1007/s00426-015-0677-6

Cipora, K., & Nuerk, H.-C. (2013). Is the SNARC effect related to the level of mathematics? No systematic relationship observed despite more power, more repetitions, and more direct assessment of arithmetic skill. *Quarterly Journal of Experimental Psychology, 66*(10), 1974-1991. doi:10.1080/17470218.2013.772215

Cipora, K., & Wood, G. (2012, January). *Optimal power to detect (between group differences) in SNARC–Monte Carlo study.* Poster presented on the XXXth European Workshop on Cognitive Neuropsychology, Bressanone, Italy.

Cohen, J. (1983). The cost of dichotomization. *Applied Psychological Measurement, 7*, 249-253. doi:10.1177/014662168300700301

Cohen, J., & Cohen, P. (1983). *Applied multiple regression/ correlation analysis for the behavioral sciences* (2nd ed.). Hillsdale, NJ, USA: Erlbaum.

Dehaene, S., Bossini, S., & Giraux, P. (1993). The mental representation of parity and number magnitude. *Journal of Experimental Psychology: General, 122*(3), 371-396. doi:10.1037/0096-3445.122.3.371

Dehaene, S., Dupoux, E., & Mehler, J. (1990). Is numerical comparison digital: Analogical and symbolic effects in two-digit number comparison? *Journal of Experimental Psychology: Human Perception and Performance, 16*, 626-641. doi:10.1037/0096-1523.16.3.626

Dehaene, S., Piazza, M., Pinel, P., & Cohen, L. (2003). Three parietal circuits for number processing. *Cognitive Neuropsychology, 20*, 487-506. doi:10.1080/02643290244000239

Fias, W., Brysbaert, M., Geypens, F., & D' Ydewalle, G. (1996). The importance of magnitude information in numerical processing: Evidence from the SNARC effect. *Mathematical Cognition, 2*(1), 95-110. doi:10.1080/135467996387552

Fias, W., Lauwereyns, J., & Lammertyn, J. (2001). Irrelevant digits affect feature-based attention depending on the overlap of neural circuits. *Cognitive Brain Research, 12*(3), 415-423. doi:10.1016/S0926-6410(01)00078-7

Fischer, M. H. (2001). Number processing induces spatial performance biases. *Neurology, 57*(5), 822-826. doi:10.1212/WNL.57.5.822

Fischer, M. H., Castel, A. D., Dodd, M. D., & Pratt, J. (2003). Perceiving numbers causes spatial shifts of attention. *Nature Neuroscience, 6*, 555-556. doi:10.1038/nn1066

Fischer, M. H., & Shaki, S. (2014). Spatial associations in numerical cognition – From single digits to arithmetic. *Quarterly Journal of Experimental Psychology, 67*, 1461-1483. doi:10.1080/17470218.2014.927515

Geiser, C., Lehmann, W., & Eid, M. (2006). Separating „rotators“ from „nonrotators“ in the Mental Rotations Test: A multigroup latent class analysis. *Multivariate Behavioral Research, 41*, 261-293. doi:10.1207/s15327906mbr4103_2

Georges, C., Hoffmann, D., & Schiltz, C. (2016). How math anxiety relates to number–space associations. *Frontiers in Psychology, 7*, Article 1401. doi:10.3389/fpsyg.2016.01401

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

Gevers, W., Santens, S., Dhooge, E., Chen, Q., Van den Bossche, L., Fias, W., & Verguts, T. (2010). Verbal-spatial and visuospatial coding of number-space interactions. *Journal of Experimental Psychology: General, 139*(1), 180-190. doi:10.1037/a0017688

Gevers, W., Verguts, T., Reynvoet, B., Caessens, B., & Fias, W. (2006). Numbers and space: A computational model of the SNARC effect. *Journal of Experimental Psychology: Human Perception and Performance, 32*(1), 32-44. doi:10.1037/0096-1523.32.1.32

Gibson, L. C., & Maurer, D. (2016). Development of SNARC and distance effects and their relation to mathematical and visuospatial abilities. *Journal of Experimental Child Psychology, 150*, 301-313. doi:10.1016/j.jecp.2016.05.009

Gilmore, C., Keeble, S., Richardson, S., & Cragg, L. (2015). The role of cognitive inhibition in different components of arithmetic. *ZDM, 47*(5), 771-782. doi:10.1007/s11858-014-0659-y

Ginsburg, V., & Gevers, W. (2015). Spatial coding of ordinal information in short- and long-term memory. *Frontiers in Human Neuroscience, 9*, Article 8. doi:10.3389/fnhum.2015.00008

Hagquist, C., & Stenbeck, M. (1998). Goodness of fit in regression analysis – R^2 and G^2 reconsidered. *Quality & Quantity, 32*, 229-245. doi:10.1023/A:1004328601205

Herrera, A., Macizo, P., & Semenza, C. (2008). The role of working memory in the association between number magnitude and space. *Acta Psychologica, 128*, 225-237. doi:10.1016/j.actpsy.2008.01.002

Hoffmann, D., Hornung, C., Martin, R., & Schiltz, C. (2013). Developing number-space associations: SNARC effects using a colour-discrimination task in 5 year olds. *Journal of Experimental Child Psychology, 116*, 775-791. doi:10.1016/j.jecp.2013.07.013

Hoffmann, D., Mussolin, C., Martin, R., & Schiltz, C. (2014). The impact of mathematical proficiency on the number-space association. *PLOS ONE, 9*(1), Article e85048. doi:10.1371/journal.pone.0085048

Hoffmann, D., Pigat, D., & Schiltz, C. (2014). The impact of inhibition capacities and age on number-space associations. *Cognitive Processing, 15*, 329-342. doi:10.1007/s10339-014-0601-9

Imbo, I., Brauwer, J. D., Fias, W., & Gevers, W. (2012). The development of the SNARC effect: Evidence for early verbal coding. *Journal of Experimental Child Psychology, 111*(4), 671-680. doi:10.1016/j.jecp.2011.09.002

Irwin, J. R., & McClelland, G. H. (2003). Negative consequences of dichotomizing continuous predictor variables. *JMR, Journal of Marketing Research, 40*, 366-371. doi:10.1509/jmkr.40.3.366.19237

Ito, Y., & Hatta, T. (2004). Spatial structure of quantitative representation of numbers: Evidence from the SNARC effect. *Memory & Cognition, 32*, 662-673. doi:10.3758/BF03195857

Jager, G., & Postma, A. (2003). On the hemispheric specialization for categorical and coordinate spatial relations: A review of the current evidence. *Neuropsychologia, 41*, 504-515. doi:10.1016/S0028-3932(02)00086-6

Kozhevnikov, M., Blazhenkova, O., & Becker, M. (2010). Trade-off in object versus spatial visualization abilities: Restriction in the development of visual processing resources. *Psychonomic Bulletin & Review, 17*, 29-35. doi:10.3758/PBR.17.1.29

Kozhevnikov, M., Chen, J. Y., & Blazhenkova, O. (2013). Creativity, visualization abilities, and visual cognitive style. *The British Journal of Educational Psychology, 83*, 196-209. doi:10.1111/bjep.12013

Kozhevnikov, M., Kosslyn, S. M., & Shephard, J. (2005). Spatial versus object visualizers: A new characterization of visual cognitive style. *Memory & Cognition, 33*, 710-726. doi:10.3758/BF03195337

Lamm, C., Bauer, H., Vitouch, O., & Gstättner, R. (1999). Differences in the ability to process a visuo-spatial task are reflected in event-related slow cortical potentials of human subjects. *Neuroscience Letters, 269*, 137-140. doi:10.1016/S0304-3940(99)00441-3

Lammertyn, J., Fias, W., & Lauwereyns, J. (2002). Semantic influences on feature-based attention due to overlap of neural circuits. *Cortex, 38*, 878-882. doi:10.1016/S0010-9452(08)70061-3

Loetscher, T., Schwarz, U., Schubiger, M., & Brugger, P. (2008). Head turns bias the brain's internal random generator. *Current Biology, 18*(2), R60-R62. doi:10.1016/j.cub.2007.11.015

Maxwell, S. E., & Delaney, H. D. (1993). Bivariate median-splits and spurious statistical significance. *Psychological Bulletin, 113*, 181-190. doi:10.1037/0033-2909.113.1.181

McKelvie, S. J. (1994). Guidelines for judging the psychometric properties of imagery questionnaires as research instruments: A quantitative proposal. *Perceptual and Motor Skills, 79*, 1219-1231. doi:10.2466/pms.1994.79.3.1219

Mitchell, T., Bull, R., & Cleland, A. A. (2012). Implicit response-irrelevant number information triggers the SNARC effect: Evidence using a neural overlap paradigm. *Quarterly Journal of Experimental Psychology, 65*(10), 1945-1961. doi:10.1080/17470218.2012.673631

Motes, M. A., Malach, R., & Kozhevnikov, M. (2008). Object processing neural efficiency differentiates object from spatial visualizers. *Neuroreport, 19*, 1727-1731. doi:10.1097/WNR.0b013e328317f3e2

Moyer, R. S., & Landauer, T. K. (1967). Time required for judgements of numerical inequality. *Nature, 215*(5109), 1519-1520. doi:10.1038/2151519a0

Nuerk, H.-C., Iversen, W., & Willmes, K. (2004). Notational modulation of the SNARC and the MARC (Linguistic Markedness of Response Codes) effect. *Quarterly Journal of Experimental Psychology, Section A: Human Experimental Psychology, 57*(5), 835-863. doi:10.1080/02724980343000512

Nuerk, H.-C., Wood, G., & Willmes, K. (2005). The universal SNARC effect: The association between number magnitude and space is amodal. *Experimental Psychology, 52*(3), 187-194. doi:10.1027/1618-3169.52.3.187

Nunnally, J. C. (1978). *Psychometric theory* (2nd ed.). New York, NY, USA: McGraw Hill.

Osborne, J. W., Christensen, W. R., & Gunter, J. (April, 2001). *Educational psychology from a statistician's perspective: A review of the power and goodness of educational psychology research.* Paper presented at the national meeting of the American Education Research Association (AERA), Seattle, WA, USA.

Osborne, J. W., & Waters, E. (2002). Four assumptions of multiple regression that researchers should always test. *Practical Assessment, Research & Evaluation, 8*(2). Retrieved from http://pareonline.net/getvn.asp?v=8&n=2

Patro, K., & Haman, M. (2012). The spatial-numerical congruity effect in preschoolers. *Journal of Experimental Child Psychology, 111*, 534-542. doi:10.1016/j.jecp.2011.09.006

Peters, M., Laeng, B., Latham, K., Jackson, M., Zaiyouna, R., & Richardson, C. (1995). A redrawn Vandenberg & Kuse Mental Rotations Test: Different versions and factors that affect performance. *Brain and Cognition, 28*, 39-58. doi:10.1006/brcg.1995.1032

Pinhas, M., Tzelgov, J., & Ganor-Stern, D. (2012). Estimating linear effects in ANOVA designs: The easy way. *Behavior Research Methods, 44*, 788-794. doi:10.3758/s13428-011-0172-y

Pitta-Pantazi, D., Sophocleous, P., & Christou, C. (2013). Spatial visualizers, object visualizers and verbalizers: Their mathematical creative abilities. *ZDM - The International Journal on Mathematics Education, 45*(2), 199-213. doi:10.1007/s11858-012-0475-1

Priftis, K., Zorzi, M., Meneghello, F., Marenzi, R., & Umilta, C. (2006). Explicit versus implicit processing of representational space in neglect: Dissociations in accessing the mental number line. *Journal of Cognitive Neuroscience, 18*(4), 680-688. doi:10.1162/jocn.2006.18.4.680

Proctor, R. W., & Cho, Y. S. (2006). Polarity correspondence: A general principle for performance of speeded binary classification tasks. *Psychological Bulletin, 132*(3), 416-442. doi:10.1037/0033-2909.132.3.416

Restle, F. (1970). Speed of adding and comparing numbers. *Journal of Experimental Psychology, 83*(2, Pt. 1), 274-278. doi:10.1037/h0028573

Rubinsten, O., & Henik, A. (2005). Automatic activation of internal magnitudes: A study of developmental dyscalculia. *Neuropsychology, 19*, 641-648. doi:10.1037/0894-4105.19.5.641

Shaki, S., & Fischer, M. H. (2008). Reading space into numbers – A cross-linguistic comparison of the SNARC effect. *Cognition, 108*, 590-599. doi:10.1016/j.cognition.2008.04.001

Shaki, S., Fischer, M. H., & Petrusic, W. M. (2009). Reading habits for both words and numbers contribute to the SNARC effect. *Psychonomic Bulletin & Review, 16*, 328-331. doi:10.3758/PBR.16.2.328

Shalev, R. S., Manor, O., Kerem, B., Ayali, M., Badichi, N., Friedlander, Y., & Gross-Tsur, V. (2001). Developmental dyscalculia is a familial learning disability. *Journal of Learning Disabilities, 34*, 59-65. doi:10.1177/002221940103400105

Tzelgov, J., Zohar-Shai, B., & Nuerk, H.-C. (2013). On defining quantifying and measuring the SNARC effect. *Frontiers in Psychology, 4*, Article 302. doi:10.3389/fpsyg.2013.00302

van Dijck, J.-P., & Fias, W. (2011). A working memory account for spatial–numerical associations. *Cognition, 119*, 114-119. doi:10.1016/j.cognition.2010.12.013

van Dijck, J.-P., Gevers, W., & Fias, W. (2009). Numbers are associated with different types of spatial information depending on the task. *Cognition, 113*(2), 248-253. doi:10.1016/j.cognition.2009.08.005

van Dijck, J.-P., Gevers, W., Lafosse, C., & Fias, W. (2012). The heterogeneous nature of number-space interactions. *Frontiers in Human Neuroscience, 5*, Article 182. doi:10.3389/fnhum.2011.00182 van Galen, M. S., & Reitsma, P. (2008). Developing access to number magnitude: A study of the SNARC effect in 7- to 9-year-olds. *Journal of Experimental Child Psychology, 101*(2), 99-113. doi:10.1016/j.jecp.2008.05.001

van Garderen, D. (2006). Spatial visualization, visual imagery, and mathematical problem solving of students with varying abilities. *Journal of Learning Disabilities, 39*(6), 496-506. doi:10.1177/00222194060390060201

Viarouge, A., Hubbard, E. M., & McCandliss, B. D. (2014). The cognitive mechanisms of the SNARC effect: An individual differences approach. *PLOS ONE, 9*(4), Article e95756. doi:10.1371/journal.pone.0095756

Wood, G., Willmes, K., Nuerk, H.-C., & Fischer, M. H. (2008). On the cognitive link between space and number: A meta-analysis of the SNARC effect. *Psychological Science Quarterly, 50*(4), 489-525.

Wu, A. D., & Zumbo, B. D. (2008). Understanding and using mediators and moderators. *Social Interactors Research, 87*, 367-392. doi:10.1007/s11205-007-9143-1

Zorzi, M., Bonato, M., Treccani, B., Scalambrin, G., Marenzi, R., & Priftis, K. (2012). Neglect impairs explicit processing of the mental number line. *Frontiers in Human Neuroscience, 6*, Article 125. doi:10.3389/fnhum.2012.00125

Appendix – SNARC Effect Size

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 Table A.1 respectively.

Table A.1

Correlation Analysis

Cognitive variables	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.

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, see Table A.2, magnitude SNARC effect sizes as DV: R^2 = .11, F(4, 76) = 2.3, p = .07, see Table A.3).

PsychOpen
publishing psychology

Moreover, the parity SNARC effect sizes were not significantly predicted by any of the numerical or spatial factors included in the regression model (see Table A.2). 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, see Table A.3). The latter finding is in line with the regression analysis on magnitude SNARC regression slopes.

Table A.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.

Table A.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.

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 (ΔR^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.