RESEARCH ARTICLE

The Attentional-SNARC effect 16 years later: no automatic space–number association (taking into account finger counting style, imagery vividness, and learning style in 174 participants)

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Abstract

The Attentional-SNARC effect (Att-SNARC) originally described by Fischer et al. (Nat Neurosci 6(6):555, 2003), consists of faster RTs to visual targets in the left side of space when these are preceded by small-magnitude Arabic cues at central fixation and by faster RTs to targets in the right side of space when these are preceded by large-magnitude cues. Verifying the consistency and reliability of this effect is important, because the effect would suggest an inherent association between the representation of space and that of number magnitude, while a number of recent studies provided no positive evidence in favour of the Att-SNARC and the inherency of this association (van Dijck et al. in Q J Exp Psychol 67(8):1500–1513, 2014; Zanolie and Pecher in Front Psychol 5:987, 2014; Fattorini et al. in Cortex 73:298–316, 2015; Pinto et al. in Cortex, DOI:10.1016/j.cortex.2017.12.015, 2018). Here, we re-analysed Att-SNARC data that we have collected in 174 participants over different studies run in our laboratory. Most important, in a subsample of 79 participants, we also verified whether the strength and reliability of the Att-SNARC is eventually linked inter-individual variations in finger counting style, imagery vividness, and verbal/visual learning style. We found no evidence for the Att-SNARC effect or for the influence of finger counting style, imagery vividness, and learning style on its direction or consistency. These results confirm no inherent link between orienting of spatial attention and representation of number magnitudes. We propose that this link is rather determined by the joint use of spatial and number magnitude or parity codes in the performance of the numerical task at hand.

Keywords Attentional SNARC · Numerical cognition · Space–number association · Individual differences

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Introduction

One of the most important and debated issues in the study of numerical cognition is whether the representation of number magnitude has an inherent spatial component or not. The idea of an inherent link between space and numbers was prompted by the discovery of the SNARC effect (*Spatial Numerical Association of Response Codes*, Dehaene et al. 1990, 1993), in which small number magnitudes are responded faster with response keys in the left side of the space and large magnitudes with response keys in the right side of the space. Despite different interpretations of the SNARC effect were proposed (for review see Cohen Kadosh et al. 2008; Wood et al. 2008; Fattorini et al. 2016), the description in 2003 of the Attentional-SNARC effect by Fischer and colleagues (2003) reinforced the assumption of a tight and inherent association between space and numbers. In their study, these authors showed that healthy participants

provide faster unimanual Reaction Times (RTs) in response to targets in the left side of space when these are preceded at central fixation by small-magnitude Arabic numbers, e.g., 1 or 2, and, vice versa, faster RTs to targets in the right side of space when these are preceded by large-magnitude numbers, e.g. 8 or 9. This effect was found despite participants were informed that digit-cues were irrelevant to target detection and did not predict target location.

During the last 16 years since the initial report by Fischer and colleagues (2003), investigations have provided conflicting results and interesting qualifications of the experimental conditions that might induce the appearance of the space–number association in the Att-SNARC task. Ristic et al. (2006) and Galfano et al. (2006) showed that the Att-SNARC could be reversed just by asking participants to imagine a mental number line (MNL) running in the right-to-left rather than left-to-right direction or by asking participants to shift their attention to the left in response to large numbers and to the right in response to small numbers. These results suggest that, whenever found, the Att-SNARC could be driven or influenced by strategic top-down factors. In a replication study co-authored by one of the authors (Dodd et al. 2008) of the initial work by Fischer and co-workers, a significant Att-SNARC was found only in one of the two temporal cue–target intervals that were used in the study by Fischer et al. (2003).

More recently, studies that have tested the Att-SNARC in adequately large samples of participants have failed to replicate the original effect. Based on the effect sizes observed by Fischer et al. (2003), van Dijck et al. (2014) estimated, "a priori", that the number of participants that would have been necessary to reach a power of 0.90 was 31. These authors tested 43 participants and found no Att-SNARC. In addition, Zanolie and Pecher (2014) found no Att-SNARC in two experiments that included a total of 44 participants. In a study run in a sample of 60 participants (Fattorini et al. 2015), we have investigated whether inter-individual variations in the strength of the Att-SNARC were eventually correlated with corresponding variations in the strength of the classical SNARC effect in Parity Judgement and Magnitude Comparison tasks. The results of our study showed no Att-SNARC effect, whereas significant and reliable SNARC effects were found in the same participants. In addition, no correlation between the Att-SNARC and the SNARC effect was found both in the whole sample of participants and when the same participants were divided in the subsamples of those showing a conventional or a reversed Att-SNARC. In two other ensuing studies (Fattorini et al. 2016; Pinto et al. 2018), we failed again to observe the Att-SNARC.

Studies run with partially modified versions of the original Att-SNARC task, have also provided conflicting results. Using a task in which left- or right-response keys had to be pressed as a function of the colour of lateral targets, which is

a procedure that introduces the use of contrasting left/right spatial codes in response selection, Goffaux et al. (2012) and Schuller et al. (2015) provided negative and positive evidence for the presence of the Att-SNARC, respectively. Finally, using a task in which lateral targets were preceded by central numerical cues (1, 2, 8, and 9) or by left- or right-pointing arrows that introduced spatial codes in the mental task set, Ranzini et al. (2009) found an Att-SNARC effect that only approached statistical significance (i.e., $p = 0.06$).

Here, we wished to re-evaluate the consistency and reliability of the Att-SNARC through the re-analysis of data that we have gathered in different investigations, run with similar procedure and stimuli in a total sample of 174 participants (Fattorini et al. 2015, 2016; Pinto et al. 2017, 2018). Most important, in a subsample of 79 participants, we investigated whether the Att-SNARC is eventually influenced by inter-individual variations in finger counting style, imagery vividness, and verbal/visual learning style. The influence of finger counting style, i.e., the preference of start counting with the left or the right hand, was envisaged by Fischer and Knops (2014) to explain the discrepancy between the significant Att-SNARC effect found by Fischer et al. (2003) in Canadian participants and the negative results reported by Zanolie and Pecher (2014) in Dutch participants. Based on data by Lindemann et al. (2011), Fischer and Knops (2014) advanced the hypothesis that these discrepant findings could be accounted on the fact that finger counting is more left-associated in Canada compared to Holland. Although data reported by Lindemann et al. (2011, Fig. 2) indicate only a very negligible difference between Canadian and Dutch participants (around 70% of left starters in both groups), in the same study, it was reported that the preference of Italian participants was equally distributed between left and right starters (i.e., around 50% in both cases). For this reason, we thought that it would have been important to test the role of finger counting style on the strength and direction of the Att-SNARC effect that we have measured in Italian participants.

Starting from the seminal observations by Francis Galton (1880a, b) several investigators have highlighted that spatially organised Mental Number Lines can be experienced in the form of vivid mental images both in participants with number-synaesthesia and in normal healthy participants (Bertillon 1880, 1881, 1882; Seron et al. 1992; Sagiv et al. 2006; Eagleman 2009). To our knowledge, however, the relationship between inter-individual variations in the vividness of visual imagery and the automaticity of the number–space interaction that should putatively highlighted in the Att-SNARC task has never been formally tested. To fill this gap, here, we used the Vividness of Visual Imagery Questionnaire (VVIQ, Marks 1973) and the Verbal and Visual Learning Styles Questionnaire (VVQ, Kirby et al. 1988) to investigate whether the vividness of visual imagery and/

or the prevalence of visual over verbal learning strategies modulates the strength of the Att-SNARC effect.

General method

Participants

One hundred and seventy-four right-handed healthy students (105 females, 69 males; mean age = 22.6 years, SD = 2.1 years) from the University "La Sapienza" in Rome were tested with the Att-SNARC task. These participants come from the whole samples of participants considered in Fattorini et al. (2015, 2016); Pinto et al. (2018) and from 26 participants to an ongoing fMRI study (Pinto et al. 2017). All participants had normal or corrected to normal vision and were naive to the experimental hypothesis. Within 1 week from the completion of experimental sessions, all participants were contacted again and asked to complete finger counting style, imagery vividness, and visual-verbal learning style questionnaires. Seventy-nine participants accepted to complete these questionnaires.

Apparatus

All experiments were run in a sound attenuated room with dim illumination. Stimuli were presented on a 15-inch-colour VGA monitor. An IBM-compatible PC running MATLAB software controlled the presentation of stimuli and the recording of responses. Participants had their head positioned on a chin rest at a viewing distance of 57.7 cm from the screen.

Assessment of counting direction style, imagery vividness, and learning styles

All three questionnaires were administered individually. Counting direction style was assessed using the same method of Lindemann and colleagues (2011). Participants were asked to count from 1 to 10 using both hands and then report in which order they used fingers to count. The Vividness of Visual Imagery Questionnaire (VVIQ, Marks 1973) provided measures of imagery vividness. Participants were asked to visualise four different mental images and then reported how well they managed to visualise four different parts of these images using a Likert scale ranging from 1 (no image) to 5 (perfect and clear image). Total score range is 1–20. Individual learning preference was assessed through the Verbal and Visual Learning Styles Questionnaire (VVQ, Kirby et al. 1988). Participants had to judge 20 statements (10 for the Verbal scale and 10 for the Visual one; e.g., "I find maps helpful in finding my way around a new city") using a Likert scale ranging from 1 (total disagreement) to 5

(total agreement). Each participant obtained one score on the Verbal preference scale and one score on the Visual preference scale. Score range for both Verbal and Visual learning style is 1–50.

Att-SNARC task

All participants were required to give unimanual speeded responses to attentional targets that were randomly flashed to the left or to the right of a central fixation cross. Lateral targets were preceded by a low- (1, 2) or a high-magnitude (8, 9) Arabic digit-cue that was presented at fixation. Digit-cues did not predict target-side and each digit-cue was followed by a target in the left side of space in 50% of trials and by a target on the right side in the remaining trials. No active cognitive processing of the digit-cue was required to participants (Fischer et al. 2003). Each trial started with the 500 ms presentation of a central fixation cross (0.4° × 0.4°) together with two lateral boxes (1° × 1°). One box was centred 5° to the left and the other 5° to the right of central fixation. At the end of this period, one out of four digit-cues (i.e., 1, 2, 8, or 9; size: 0.8° × 0.6°) was presented for 300 ms at central fixation. Cue presentation was followed by a 500 ms or 750 ms cue–target interval (CTI). At the end of the CTI, a white asterisk-target (0.5° × 0.5°) was randomly presented inside one of the two lateral boxes for 100 ms. Participants signalled as soon as possible target detection by pressing with the right index finger the central bar of a computer keyboard. In the re-analysis of data reported in the present study, we only considered RTs observed with 500 ms and 750 ms CTI, because in the original study by Fischer and co-workers, these CTIs were those at which the Att-SNARC effect was maximal. Please note that with the exception of one of the experiments reported in Fattorini et al. (2015) where all the four CTIs used in Fischer et al. (2003; Experiment 2) were used and no Att-SNARC was found in a sample of 32 participants, all data that were re-analysed in the present study were gathered from experiments that were run using intermixed trials with 500 ms and 750 ms CTIs. In Fattorini et al. (2015, 2016), we used 24 repetitions for each experimental condition (e.g., digit-cue "1 "/left target/CTI 500 ms) and 12 catch trials for each digit-cue and CTI. In Pinto et al. (2017), we used 24 repetitions for each experimental condition and 6 catch trials for each digit-cue and CTI. Finally in Pinto et al. (2018), we used 28 repetitions for each experimental condition and 4 catch trials for each digit-cue and CTI.

Statistical analyses

. The Att-SNARC effect was initially assessed in the entire sample of 174 participants, using two methods: first, by entering individual mean RTs in a Digit-Cue (Smaller, Larger) × Target-Side (Left, Right) × CTI (500, 750 ms)

ANOVA; second, using regression analyses (Lorch and Myers 1990). In this case, individual differential RTs (dRTs) were initially calculated by subtracting the average RTs recorded in trials with left-side targets from average RTs recorded in trials with right-side targets. Then, we estimated individual linear regression slopes using digit magnitude as the predictor variable and dRTs as the criterion variable (Fattorini et al. 2015). Using this method, a negative slope that differs significantly from zero highlights a significant Att-SNARC (Fias 1996; Ito and Hatta 2004).

We also performed Bayesian hypothesis testing using JASP (JASP Team 2018) (version 0.10.0.0). Bayesian analyses (one-sample t test) were run using individual linear regression slopes tested against 0. Since we were interested in testing how much the null hypothesis was favoured against the alternative one, we report only BF_{01} values provided by JASP. Our directional prediction for this type of analysis was that the individual linear regression slopes would have been significantly lower than 0.

For each questionnaire, the whole group of participants that completed the questionnaires was split in two sub-samples. For finger counting style, participants were split into the subsample of those having left-to-right and those having right-to-left preference. For imagery vividness, we calculated individual scores and then, based on the median score of all participants, we classified participants into the subgroups with "high imagery vividness" (i.e., participant with scores higher than the group median score) and "low imagery vividness" (i.e., participants with scores lower than the group median score). Visual and verbal learning scores were analysed separately. For each learning style, based on the median score of the whole group, participants were classified as having "high" or "low" score. In this way, we created subgroups of participants with high or low visual learning style and subgroups with high or low verbal learning style. For each questionnaire, the Att-SNARC effects observed in each of the two subsamples were compared both through a series of Group × Digit-Cue (Smaller, Larger) × Target-Side (Left, Right) × CTI (500, 750 ms) ANOVAs and by contrasting the average slope values of each subgroup through two-tailed t tests. Finally, we studied the correlations between the strength of the Att-SNARC effect, reflected in the individual dRTs slopes, and the scores in the VVQ and VVIQ. In addition, we also run a series of analysis considering the scores from the VVIQ and the VVQ questionnaires as a continuous predictor variable.

Results

Attentional-SNARC task

In the whole sample 174 of participants, the Digit-Cue (Smaller, Larger) × Target-Side (Left, Right) × CTI (500, 750 ms) ANOVA highlighted no significant Att-SNARC [Digit-Cue × Target-Side interaction: $F(1, 173) = 1.41$, $p = 0.24$, $\eta^2 < 0.01$]. CTI had no influence on Att-SNARC [Digit-Cue × Target-Side × CTI interaction: $F(1, 171) = 0.38$, $p = 0.54$, $\eta^2 < 0.01$] (Fig. 1a, b). In addition, we found a significant difference in CTI [$F(1, 173) = 7.87$, $p < 0.01$, $\eta_p^2 = 0.05$], in particular participants obtained faster RTs in the 750 conditions (412 ms) compared to 500 (415 ms). No other main or interaction effects were statistically significant (all $p > 0.40$). One-sample t test showed that in the entire sample of 174 participants, the dRTs' regression slope was not significantly different from zero [$t(173) = 1.30$, $p = 0.21$, $d = 0.10$; average $= 0.26$, SD $= 2.59$] (Fig. 1c). The Bayesian one-sample t test showed a BF_{01} of 26.02, indicating that the null hypothesis is 26.02 more favoured than the alternative one, given the data, thus confirming the absence of the Att-SNARC effect. An illustration of the effects of assigning a range of different prior distributions (i.e., a Bayes factor robustness check) is presented in Fig. 1d and e.

No Att-SNARC was also observed in the sample of 79 participants that accepted to complete the questionnaires [Digit-Cue × Target-Side interaction: $F(1, 77) = 3.42$, $p = 0.07$, $\eta_p^2 = 0.04$; Regression slope: $t(78) = 1.24$, $p = 0.22$, $d = 0.14$; average $= 0.37$, SD $= 2.67$]. No other main or interaction effects were statistically significant (all $p > 0.12$). The Bayesian one-sample t test showed a BF_{01} of 17.08, suggesting that the null hypothesis is 17.08 more favoured than the alternative one.

Finger counting style

Forty-two participants showed left-to-right and thirty-seven showed right-to-left preference. Both the Group × Digit-Cue × Target-Side interaction [$F(1, 77) = 1.64$, $p = 0.20$, $\eta_p^2 = 0.02$] and the Group × Digit-Cue × Target-Side × CTI interaction [$F(1, 77) = 0.34$, $p = 0.85$, $\eta_p^2 < 0.01$] were not significant (Fig. 2a, b). These results show no Att-SNARC in both groups and no influence of finger counting style on the Att-SNARC. No other main effect or interaction was statistically significant (all $p > 0.22$). These conclusions were also confirmed by regression [Group Left-to-Right: $t(41) = 1.20$, $p = 0.23$, $d = 0.18$; average $= 0.54$, SD $= 2.93$; Group Right-to-Left: $t(36) = 0.45$, $p = 0.65$, $d = 0.08$; average $= 0.18$, SD $= 2.35$; comparison between two groups: $t(77) = 0.61$, $p = 0.54$, $d = 0.14$; Fig. 2c] and Bayesian
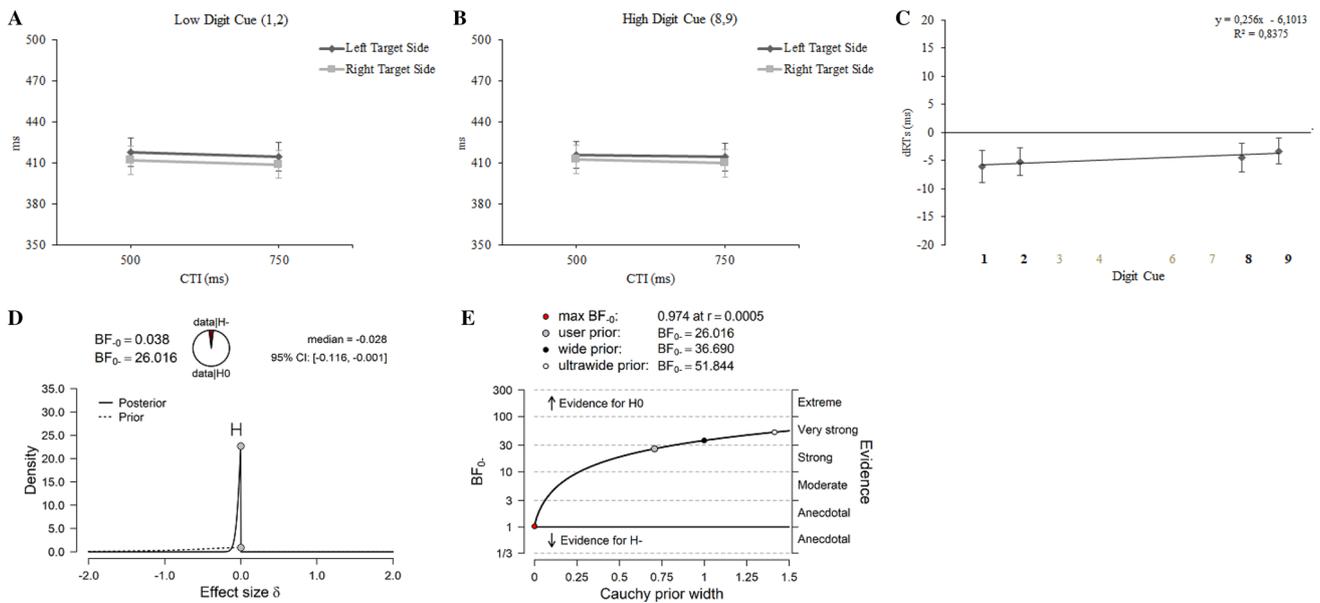
Fig. 1 All participants. Average RTs (with SE) to targets presented in the left and right sides of space plotted as a function of the magnitude of central digit-cues, i.e., **a** Low (1,2) or **b** High (8,9), and Cue–Target Interval. **c** Slope describing the difference between RTs to targets in the right side of space minus targets in the left side of space (dRTs in ms), plotted as a function of the magnitude of central digit-cues. **d** The prior and posterior distribution plot for a directional analysis of linear regression slopes. **e** Bayesian analysis of linear regression slopes: a robustness check illustrating the effects of assigning wide and ultrawide Cauchy prior widths on Bayes factor values
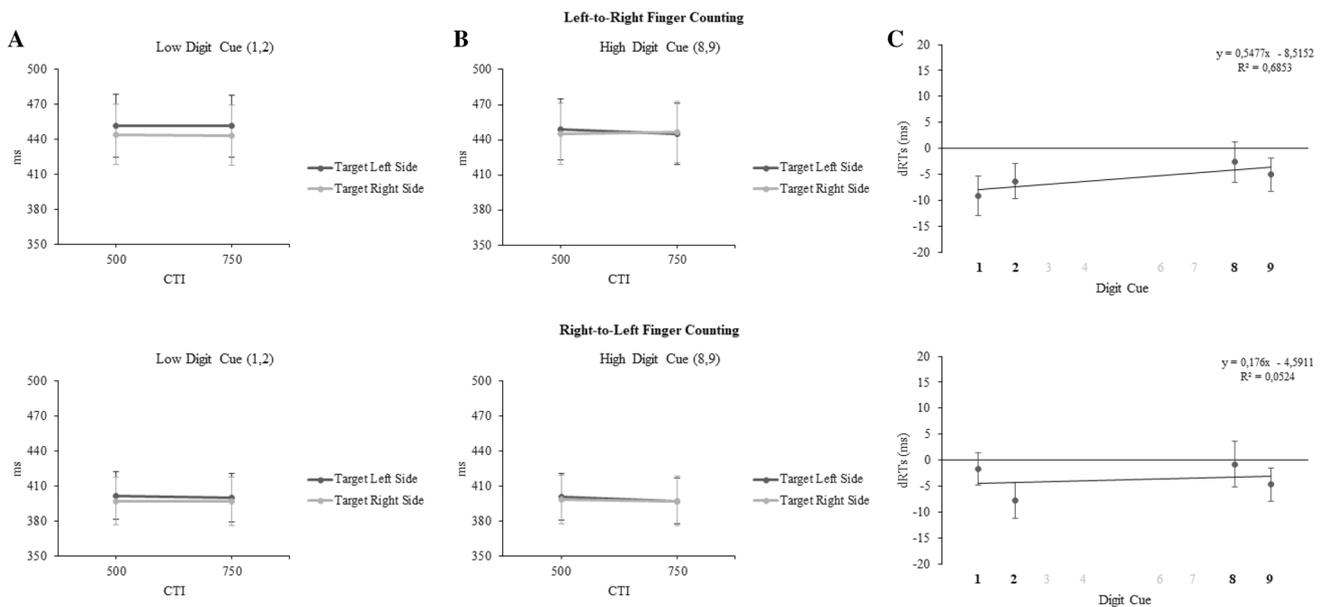
Fig. 2 Finger counting style. Average RTs (with SE) to targets presented in the left and right sides of space plotted as a function of the magnitude of central digit-cues, i.e., **a** Low (1,2) or **b** High (8,9), and Cue–Target Interval. **c** Slope describing the difference between RTs to targets in the right side of space minus targets in the left side of space (dRTs in ms), plotted as a function of the magnitude of central digit-cues. In the upper panel, are reported the results of participants with left-to-right finger counting style ($N=42$), while in the lower panel are reported the results of participants with right-to-left finger counting style ($N=37$)

analyses (Group Left-to-Right: BF_{01} of 12.30; Group Right-to-Left: BF_{01} of 7.75).
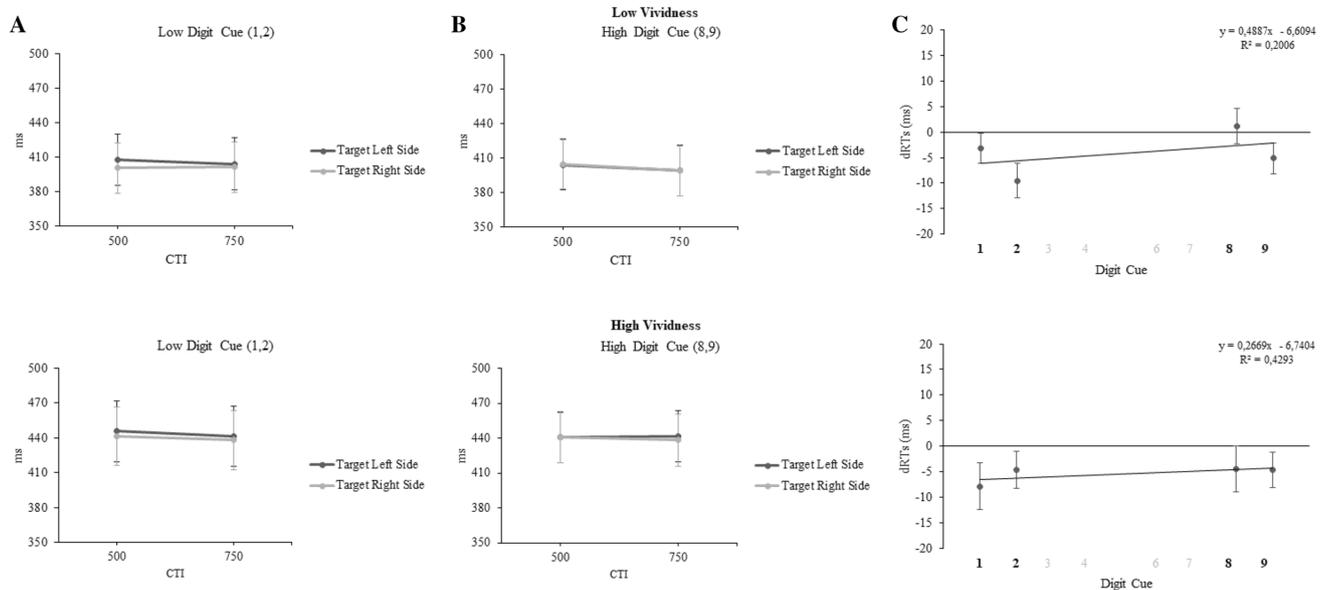
Vividness of Visual Imagery Questionnaire (VVIQ)

Forty-one participants showed low imagery vividness (Mean score = 3.5) and thirty-eight high imagery vividness (Mean score = 4.4) with respect to the median score of 4. Both the Group × Digit-Cue × Target-Side interaction [$F(1, 77) = .59$, $p = 0.44$, $\eta_p^2 = 0.02$] and the Group × Digit-Cue × Target-Side × CTI interaction [$F(1, 77) = 0.01, p = 0.99, \eta_p^2 < 0.01$] were not significant (Fig. 3a, b). These results show no Att-SNARC in both groups and no influence of imagery vividness on the Att-SNARC. No other main effect or interaction was statistically significant (all $p > 0.11$). These conclusions were also confirmed by regression (Group Low Vividness: = $t(40) = 0.56$, $p = 0.57$, $d = 0.09$; average = 0.27, SD = 3.03; Group High Vividness: $t(37) = 1.34$, $p = 0.19$, $d = 0.22$; average = 0.49, SD = 2.25; comparison between two groups: $t(77) = 0.36$, $p = 0.71$, $d = 0.08$; Fig. 3c] and Bayesian analyses [Group Low Vividness: BF_{01} of 12.39; Group High Vividness: BF_{01} of 8.69]. In line with these results, the analysis performed using questionnaire score as a continuous predictor variable showed no significant VVIQ-Score × Digit-Cue × Target-Side interaction [$F(1, 77) = 0.89$, $p = 0.34$, $\eta_p^2 = 0.01$].

## Verbal and Visual Learning Style Questionnaire (VVQ)

Forty participants showed low scores in verbal learning style (Mean score = 26.7) and thirty-nine high scores (Mean score = 31.8; median group score = 30). Both the Group × Digit-Cue × Target-Side interaction [$F(1, 77) = 0.35$, $p = 0.56$, $\eta_p^2 = 0.004$] and the Group × Digit-Cue × Target-Side × CTI interaction [$F(1, 77) = 3.29$, $p = 0.07$, $\eta_p^2 = 0.04$] were not significant (Fig. 4a, b). These results show no Att-SNARC in both groups and no influence of the verbal learning style on the Att-SNARC. No other main or interaction was statistically significant (all $p > 0.10$). These conclusions were also confirmed by regression [Group Low: = $t(39) = 0.97$, $p = 0.34$, $d = 0.15$; average = 0.35, SD = 2.27; Group High: $t(38) = 0.81$, $p = 0.82$, $d = 0.13$; average = 0.40, SD = 3.06; comparison between two groups: $t(77) = -0.038$, $p = 0.97$, $d = 0.02$; Fig. 4c] and Bayesian analyses [Group Low: BF_{01} of 10.72; Group High: BF_{01} of 9.76]. In line with these results, the analysis performed using questionnaire score as a continuous predictor variable showed no significant Verbal-Score × Digit-Cue × Target-Side interaction [$F(1, 77) = 0.08$, $p = 0.78$, $\eta_p^2 < 0.01$].

Thirty-one participants showed low scores in visual learning style (Mean score = 25.8) and forty-eight participants showed high scores (Mean score = 31.8; median group score = 30). Both the Group × Digit-Cue × Target-Side
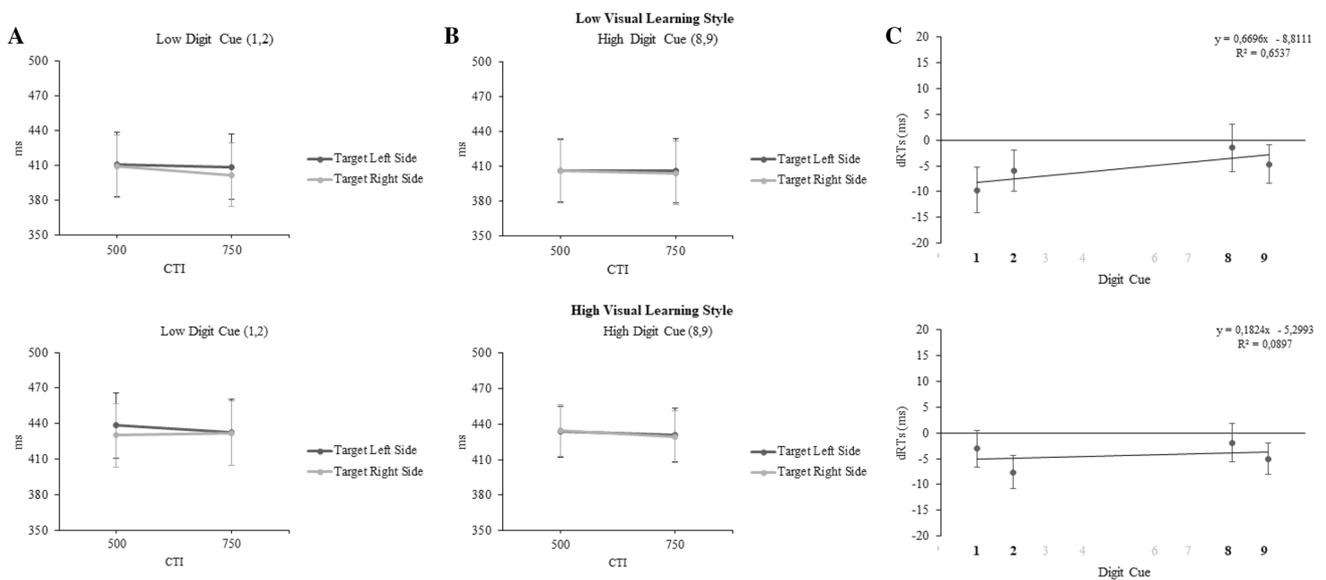
Fig. 3 Vividness of Visual Imagery Questionnaire. Average RTs (with SE) to targets presented in the left and right sides of space plotted as a function of the magnitude of central digit-cues, i.e., **a** Low (1,2) or **b** High (8,9), and Cue–Target Interval. **c** Slope describing the difference between RTs to targets in the right side of space minus targets in the left side of space (dRTs in ms), plotted as a function of the magnitude of central digit-cues. In the upper panel, are reported the results of participants with low imagery vividness ($N = 41$), while in the lower panel, are reported the results of participants with high imagery vividness ($N = 38$)
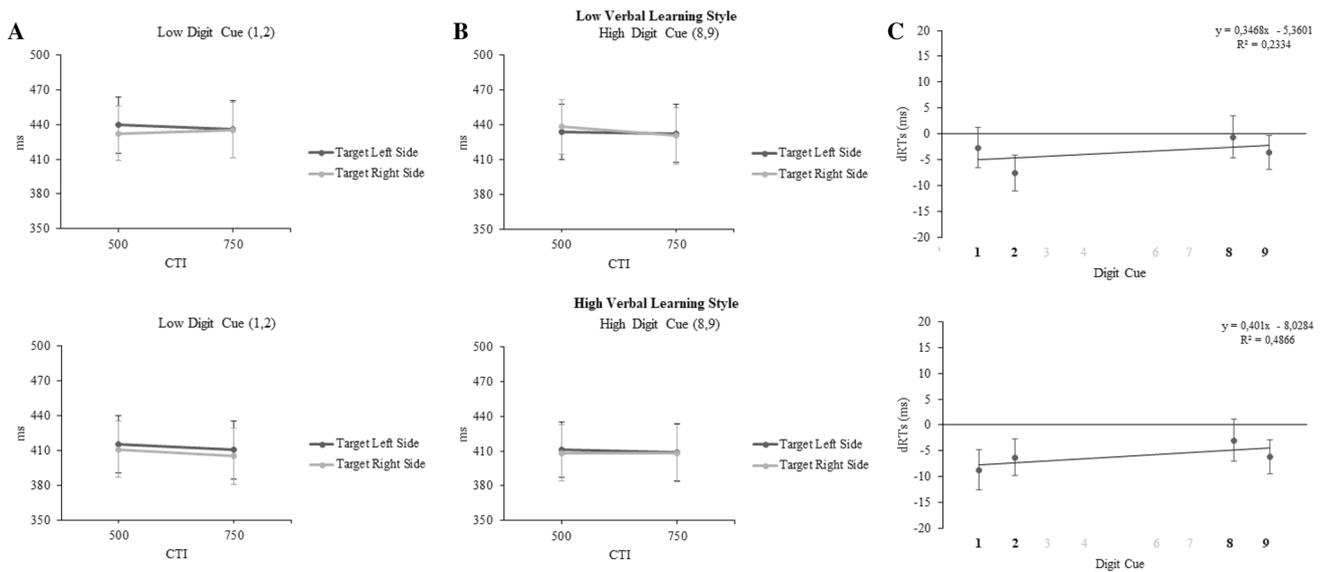
Fig. 4 Verbal learning style. Average RTs (with SE) to targets presented in the left and right sides of space plotted as a function of the magnitude of central digit-cues, i.e., **a** Low (1,2) or **b** High (8,9), and Cue–Target Interval. **c** Slope describing the difference between RTs to targets in the right side of space minus targets in the left side of space (dRTs in ms), plotted as a function of the magnitude of central digit-cues. In the upper panel, are reported the results of participants with low verbal learning style scores ($N=40$), while in the lower panel, are reported the results of participants with high verbal learning style scores ($N=39$)

Fig. 5 Visual learning style. Average RTs (with SE) to targets presented in the left and right sides of space plotted as a function of the magnitude of central digit-cues, i.e., **a** Low (1,2) or **b** High (8,9), and Cue–Target Interval. **c** Slope describing the difference between RTs to targets in the right side of space minus targets in the left side of space (dRTs in ms), plotted as a function of the magnitude of central digit-cues. In the upper panel, are reported the results of participants with low visual learning style scores ($N=31$), while in the lower panel, are reported the results of participants with high visual learning style scores ($N=48$)

interaction [$F(2, 76)=0.52$, $p=0.60$, $\eta_p^2=0.01$] and the Group × Digit-Cue × Target-Side × CTI interaction [$F(1, 77)=0.04$, $p=0.83$, $\eta_p^2<0.01$] were not significant (Fig. 5a, b). These results show no Att-SNARC in both groups and

no influence of the visual learning style on the Att-SNARC. No other main or interaction was statistically significant (all $p>0.11$). These conclusions were also confirmed by regression [Group Low: $=t(30)=1.36$, $p=0.18$, $d=0.35$; average $=0.97$, SD $=2.74$; Group High: $t(47)=0.48$, $p=0.63$,

$d = 0.07$; average $= 0.18$, SD $= 2.63$; comparison between two groups: $t(77) = 0.79$, $p = 0.43$, $d = 0.29$; Fig. 5c] and Bayesian analyses [Group Low: BF_{01} of 11.30; Group High: BF_{01} of 8.90]. In line with these results, the analysis performed using questionnaire score as a continuous predictor variable showed no significant Visual-Score × Digit-Cue × Target-Side interaction [$F(1, 77) = 0.85$, $p = 0.77$, $\eta_p^2 < 0.01$].

Correlations analyses

In these series of analyses, we evaluated Pearson-r correlations between the individual slopes defining the strength of the Att-SNARC and the individual data results in the VVIQ and in the VVQ (Table 1). Correct application of these analyses requires the assumption of multivariate normality (Barbaranelli 2007; Raykov and Marcoulides 2012). The Mahalanobis Distance was smaller than the critical value (all $p > 0.001$, critical value recommended by Tabachnick et al. 2007) showing that in our set of data, no univariate or multivariate outliers were present. In addition, we found that variables distribution was comparable to a multivariate normal (Mardia's multivariate kurtosis index $= 13,1$; p value $= 24$; Mardia 1970, 1974).

No correlation was found between the Att-SNARC and the VVIQ or the VVQ (all $p > 0.43$, see Table 1). In addition, no significant correlation was found among the scores of the different questionnaires (all $p > 0.14$, see Table 1).

Discussion

The results of the present study provide no evidence for the Att-SNARC effect in healthy participants or for the influence of finger counting style, imagery vividness, or verbal/visual learning style on the consistency or direction of the same effect. Taken together, these results suggest no automatic link between the representation of space and the representation of number magnitude in behavioural conditions where, like in the Att-SNARC task, no use of spatial response codes is required [for an extended discussion on the automatic link

between space and numbers when spatial codes are in use, see Pinto et al. 2019]. This dissociation is in agreement both with the results of recent neuroimaging mapping investigation that highlighted no overlap between the topographical representation of numerosity and the topographical representation of space in the human parietal cortex (Harvey et al. 2013) and with previous findings in right brain damaged patients with and without left spatial neglect (Doricchi et al. 2005, 2009; Aiello et al. 2012, 2013) and in healthy participants (Rotondaro et al. 2015).

Given the absence of an inherent association between space and numbers, one could ask what is the origin of reliable space–number associations as the one highlighted, for example, by the SNARC effect. The SNARC was initially interpreted as deriving from the correspondence between the inherent spatial position that numbers occupy on the mental equivalent of a left-to-right organised ruler, i.e., the Mental Number Line (MNL) and the position of response keys (for reviews, see Cohen Kadosh et al. 2008; Wood et al. 2008; Fattorini et al. 2016): the results of the present study do not support this hypothesis, because they highlight no inherent spatial coding of number magnitudes. Other authors have emphasised that the SNARC depends on a culturally based association between contrasting "left/right" and contrasting "small/large" semantic codes (Proctor and Cho 2006; Santens and Gevers 2008; Gevers et al. 2010). Within this theoretical framework, Gevers et al. (2010) highlighted the important role played by the verbal coding of spatial dimensions, by showing that when spatially incongruent verbal labels are assigned to left- and right-response keys, so that the key on the left side is labelled "right" and that on the right side is labelled "left", the SNARC effect remains anchored to verbal labels rather than to the actual position of response keys. Based on a review of studies run in patients with left spatial neglect, in recent years, we have repeatedly proposed that the space–number association does not rely on inherent semantic properties of number magnitudes but rather on the use of spatial codes in the numerical task at hand (Doricchi et al. 2005, 2009; Loetscher and Brugger

Table 1 Correlations among the Attentional-SNARC effect, the Vividness of Visual Imagery (VVIQ), and the Verbal and Visual learning styles (VVQ) (Pearson's r coefficient) in the subsample of participants ($N = 79$) with lower and upper limits of 95% Confidence Intervals inside parentheses (p value below)

$N = 79$	Att-SNARC	VVIQ	Verbal	Visual
1. Att. SNARC	–			
2. VVIQ	-0.0041 ($-0.181/0.164$) $p = 0.97$	–		
3. Verbal	0.017 ($-0.225/0.242$) $p = .88$	0.0554 ($-0.245/0.178$) $p = 0.627$	–	
4. Visual	0.0895 ($-0.157/0.319$) $p = 0.43$	-0.0298 ($-0.215/0.168$) $p = 0.794$	-0.1674 ($-0.326/0.017$) $p = 0.140$	–

2009; Loetscher et al. 2010; Rossetti et al. 2011; van Dijck et al. 2011, 2012; Pia et al. 2012; Aiello et al. 2012, 2013).

In particular, we emphasised that while no systematic association is found between left spatial neglect and the numerical bias in mental bisection of number intervals, which is a task that is performed without using left/right spatial response codes, during the performance of an SNARC task which requires the use of left/right spatial codes for response selection, patients with neglect show a systematic delay in judging the magnitude of numbers that are immediately lower than a given numerical reference, e.g., 4 with respect to 5, just as if these numbers were mentally positioned to the left of the reference.

Expanding on this proposal, in a series of studies (Fattorini et al. 2015, 2016; Pinto et al. 2018), we have demonstrated that space–number associations can be generated not only when contrasting left/right spatial codes are linked to number stimuli through response selection but also when the same spatial codes are conceptually and directly associated to number stimuli. In particular, using a variation of the Att-SNARC task, in each trial, we asked participants to report, following the speeded manual detection of lateral targets, whether the central numerical cue is conventionally mentally positioned to the left or to the right of a reference, i.e., number 5. Using this paradigm, we found that the detection of visual targets in the left side of space was speeded up by the presentation of small numerical cues, i.e., 1 or 2 conventionally lying to the left of 5, while that of targets in the right side was facilitated when these followed large numerical cues, i.e., 8 or 9 conventionally lying to the right of 5. These results provided evidence that a significant Att-SNARC effect is observed when the active use of left/spatial codes is included in the task: we called this effect Spatial Att-SNARC effect. In an ensuing study, we showed that at the electrophysiological level (Pinto et al. 2018), the active mental positioning of numbers to the left or the right of the central reference is reflected in an enhancement of facilitatory-preparatory brain activity over the hemisphere contralateral to the mental number position, i.e., Lateral Directing Attention Positivity (LDAP), and in the enhancement of early EEG responses, C1 component, to targets that are presented on the side of visual space that is congruent with that of numerical cues in mental space. Taken together, these data support our hypothesis that reliable space–number associations are found when left/right spatial codes are used in the task, and independently of the fact that they are used for response selection or they are directly conceptually associated with number magnitudes. In agreement with this proposal, Fischer and Shaki (2017) have recently demonstrated that when left/right spatial codes are used in conjunctions with magnitude codes in the instructions that regulate the release of unimanual Go responses to central small/large numerical targets that are intermixed with central arrow targets pointing to the left or to the right, a significant space–number association is found. This is suggested by

the finding that reaction times (RTs) to number and arrow targets are faster when spatial and numerical codes defining the release of Go responses are conceptually congruent, e.g., go when an arrow points left or a number is lower than 5, rather than incongruent, e.g., go when an arrow points left or a number is higher than 5.

In a very recent investigation (Pinto et al. 2019), we further qualified this evidence by showing that reliable and stable space–number associations are elicited *only* when contrasting left/right spatial codes are used in conjunction with contrasting small/large-magnitude numerical ones, because these associations are no longer present or reliable when numerical magnitude or spatial codes are used in isolation (e.g., go when the number is lower than 5 and whenever an arrow appears; go when an arrow points left and whenever a number appears). Taken together, these data provide a reasonable explanation for the absence or unreliability of the space–number association in the conventional Att-SNARC task, which is a task where neither spatial nor number magnitude codes are in use.

To summarise, available evidence suggests that the space–number associations are flexible, temporary, and context-dependent rather than fixed and context independent. Here, we would like to briefly note that from an evolutionary standpoint, the existence of a flexible rather than fixed association between the representation of numbers and the representation of space seems far more adaptive, for the obvious reason that in natural settings small and large numerosities are not constantly located, respectively, to the left and to the right of an agent viewpoint. Put in other words, there is no reason to assume that a fixed and context-independent association between the brain representation of number "2" and the representation of the "left" side of space would be truly advantageous. Second, given that well-established association between the spatial organization of MNL and reading habits (Ito and Hatta 2004; Zebian 2005; Shaki and Fischer 2008; Shaki et al. 2009; Göbel et al. 2011) assuming a phylogenetically grounded left-to-right organization of the MNL would imply a disadvantageous and costly ontogenetic neural re-wiring in participants belonging to right-to-left reading cultures, who typically organise their MNL in the right-to-left direction. Finally, the absence of the SNARC effect in illiterate participants or in children under the age of nine (Berch et al. 1999; Hubbard et al. 2005) further suggest the cultural, rather than phylogenetically driven, origin of the space–number association.

The results of the present study generally challenge the idea that the ascending series of numbers is inherently organised along left-to-right or right-to-left spatial dimension and rather highlight the importance of establishing a theoretically consistent taxonomy of experimental and natural context that induce temporary and more or less stable associations between the representation of numbers and the

representation of space. As an example, van Dijck, Fias and co-workers (van Dijck and Fias 2011; Fias et al. 2011; van Dijck et al., 2013, 2014; Abrahamse et al. 2016; Fias and van Dijck 2016) showed that keeping in memory arbitrary sequence of five numerical items to monitor the ordinal position of each one of these items triggers the automatic adoption of a left-to-right mental scanning of the series that is consonant to reading habits. Although recent findings suggest that this effect might be different and co-occur with conventional SNARC effects (Ginsburg and Gevers 2015; Huber et al. 2016; Guida and Campitelli 2019), this result suggests that specific cognitive contexts and tasks, like the memorization of arbitrary sequences of multiple numerical or non-numerical items, can still determine the automatic adoption of left-to-right organised mental representations notwithstanding the explicit use of spatial or numerical codes is not required by the task. The findings reported or reviewed in the present study suggests that, in contrast, when a task requires the processing of single numerical items that are not explicitly embedded in a sequence, the joint use of spatial and numerical codes is instead required to elicit spatially organised mental number lines.

To conclude, available evidence shows that different cognitive contexts and mechanisms can determine the generation of space–number association: providing an exhaustive description and understanding of these contexts is the major challenge that future investigations should face.

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