Experimental Brain Research (2019) 237:1031–1043
https://doi.org/10.1007/s00221-019-05483-5

RESEARCH ARTICLE

Multiple left-to-right spatial representations of number magnitudes? Evidence from left spatial neglect

Jean-Philippe van Dijck[1,2] · **Fabrizio Doricchi**[3,4]

Received: 27 May 2018 / Accepted: 29 January 2019 / Published online: 9 February 2019

Abstract

The SNARC effect reflects the observation that when healthy observers with left-to-right reading habits are asked to compare the magnitude or to judge the parity of numbers, they provide faster reaction times (RT) to small numbers with left-sided responses and faster RTs to large numbers with right-sided responses. In magnitude comparison (MC), right brain damaged patients with left-sided neglect typically show a pathologically enlarged SNARC for large numbers and selective slowing to numbers that are immediately lower than the numerical reference (e.g. 4 for reference 5). This asymmetry has been taken as evidence that small numbers are mentally positioned to the left of the reference and, therefore, are processed less efficiently by patients neglecting the left side of space. In parity judgement (PJ), on the other hand, the size of the SNARC effect is unaffected by neglect. This dissociation is typically attributed to the disturbed explicit processing of number magnitude in MC and preserved implicit processing of magnitude in PJ. Before accepting this interpretation, however, it remains to be investigated whether neglect patients show the same RT pattern that characterizes the performance of healthy participants (i.e. left-side RTs that increase linearly as a function of number magnitude and right-side RTs that decrease linearly as a function of magnitude). Clarifying this point is crucial, because an equally sized SNARC can originate from different RT patterns. Here we demonstrate that the RT pattern of neglect patients during PJ is entirely comparable to those of patients without neglect and healthy controls, while the same neglect patients show selective slowing to numbers that are immediately lower than the numerical reference in MC. These findings suggest the existence of multiple left-to-right spatial representations of number magnitude and provides an explanation of the functional dissociation between MC and PJ tasks.

Keywords SNARC effect · Distance effect · Spatial neglect · Spatial codes

Introduction

Investigating the functional interaction between the mental representation of number magnitudes and the representation of space is a cornerstone in the domain of numerical cognition. The most reliable phenomenon illustrating this interaction is the SNARC effect. The SNARC effect captures the observation that manual RTs to small numbers are faster in the left side of space and RTs to large numbers faster in the right side of space (e.g. Dehaene et al. 1993). The SNARC is typically attributed to the congruency between the spatial location of the motor responses and the position that, due to reading habits, number magnitudes occupies on a mental number line with small numbers located to the left of larger ones (e.g. Hubbard et al. 2005). Some authors have proposed that the left/right spatial positioning is inherently associated to numbers (Hubbard et al. 2005) while others have argued that during the performance of SNARC tasks the mental left-to-right organization of number magnitudes is adopted because the task requires the use of contrasting left/right spatial codes in the selection of the response (Gevers et al. 2006; Schwarz and Keus 2004; Fattorini et al. 2015, 2016; Pinto et al. 2018). Finally other authors suggested that the SNARC is rooted in culturally acquired associations between

✉ Jean-Philippe van Dijck
jeanphilippe.vandijck@ugent.be

1 Department of Experimental Psychology, Ghent University, H. Dunantlaan 2, 9000 Ghent, Belgium

2 Department of Applied Psychology, Thomas More University of Applied Sciences, Molensstraat 8, Antwerp 2018, Belgium

3 Department of Psychology, Rome University “La Sapienza”, Rome, Italy

4 Fondazione Santa Lucia-IRCCS Rome, Rome, Italy

"left-small" and "right-large" semantic codes (Gevers et al. 2010; Proctor and Cho 2006).

The SNARC is usually measured in two different tasks: Magnitude Comparison (MC; e.g. is number "2" higher or lower than "5"?) and parity judgement (PJ; e.g. is number "2" an odd or even number?). Although it was initially believed that the MC and PJ task draw upon the same underlying cognitive mechanisms (for a review see Fias and Fischer 2005), a number of recent studies have pointed out that this is not necessarily the case. For example, investigating the effects of dual-task interference on the SNARC effect in healthy participants revealed that a concurrent spatial working memory task disrupts the MC SNARC but not the PJ one, while a phonological WM task affects the PJ SNARC but not the MC one (van Dijck et al. 2009). Although these dual tasks studies do not allow identifying the stage of cognitive processing at which the interference takes place (e.g. stimulus encoding, mental representation, decisional processes, response selection), they point at differences in the functional origin of both SNARC effects. This dissociation is further supported by the finding that in healthy participants the strength of the MC and PJ SNARC are not correlated (Fattorini et al. 2015).

The study of right brain damaged patients (RBD) with attentional neglect for the left side of space has provided additional clues about the functional origin of the MC and PJ SNARC. In MC the performance of healthy participant is typically characterized by a symmetrical comparison distance effect (DE), so that it takes equally long to decide that 4 or 6 are smaller and larger than the reference number 5. In contrast, in patients with neglect the DE is asymmetrical, so that RTs to numbers immediately smaller than the reference, e.g. 4 with respect to 5, are slower than RTs to numbers immediately larger than the same reference, e.g. 6 with respect to 5 (Vuilleumier et al. 2004). This result has been taken as a confirmation that the MC task triggers a left-to-right spatially organized mental number line and that patients with neglect are slower at processing numbers in the contralesional side of the mental number line. Another finding that points at the left-to-right spatial organization of numbers during the performance of the MC SNARC is that, compared to non-neglect patients and healthy controls, neglect patients show an exaggerated SNARC for large numbers (Zorzi et al. 2012). This was interpreted as a reorienting deficit. After processing a large number, it takes longer to disengage attention from the non-neglected right side of the mental number line to select manual responses in the contralesional direction. In contrast to these spatially abnormal features of the MC SNARC, it was pointed out that in neglect patients the size of the PJ SNARC is entirely normal and comparable to that of non-neglect patients and healthy controls (e.g. Priftis et al. 2006; van Dijck et al. 2012; Zorzi et al. 2012). The dissociation between the disturbed MC and the normal PJ SNARC in neglect patients was tentatively interpreted in terms of differences between explicit and implicit processing of numerical magnitude. According to this hypothesis, in MC tasks an explicit access to the representation of number magnitude is required: this type of access would elicit the left-to-right spatial representation of number magnitudes and the consequent asymmetrical distance effect with slower RTs to numbers positioned immediately to the left of the central numerical reference in patients with neglect. In contrast, PJ would require only an implicit access to the representation of number magnitude. Since the implicit processing of visual information in the neglected space can be spared in patients with neglect (see for example, Marshall and Halligan 1988; Berti and Rizzolatti 1992; Doricchi et al. 1997), no impairment in the processing of numbers positioned to the left of the central numerical reference is expected during the PJ SNARC task (Priftis et al. 2006). Though logically plausible, this interpretation remains largely hypothetical because the association between preserved implicit processing a normal parity SNARC in neglect patients remains to be empirically investigated. This step is of major importance given that not all neglect patients show preserved implicit processing of explicitly unrecognized visual information in the neglected space (see for example Table 2 in Doricchi et al. 1997). In the absence of independent evidence for the association between spared implicit processing and normal PJ in neglect, this interpretation suffers tautological circularity: It claims that PJ only requires implicit access to number magnitude because implicit access is spared in neglect patients and that the PJ SNARC is spared in neglect patients because it only requires implicit access to number magnitude.

Here we wish to consider another hypothesis: namely, that disturbed MC and spared PJ SNARC are dissociated in neglect patients because these two tasks tap on different spatial representations of number magnitudes. This hypothesis can be tested by considering a salient spatial property in the distribution of RTs in the PJ task that was systematically overlooked in previous studies. In participants without neurological deficits, the distribution of RTs in the PJ task is characterized by a specific pattern: left-side RTs increase (linearly) as a function of number magnitude while right-side RTs show a symmetrically opposite trend with a (linear) decrease as a function of number magnitude (see. Fig. 1a). So far however, the PJ SNARC in RBD patients was only investigated by comparing the size of the SNARC effect (e.g. Priftis et al. 2006; van Dijck et al. 2012), where the size of the effect is determined using linear regression. In this approach, in each patient and for each number separately, average right-side RTs are subtracted from averaged left-side RTs and the difference in RTs (dRT) is entered in a regression analysis using number magnitude as predictor. The unstandardized regression weight of the magnitude predictor obtained with this procedure is typically considered to

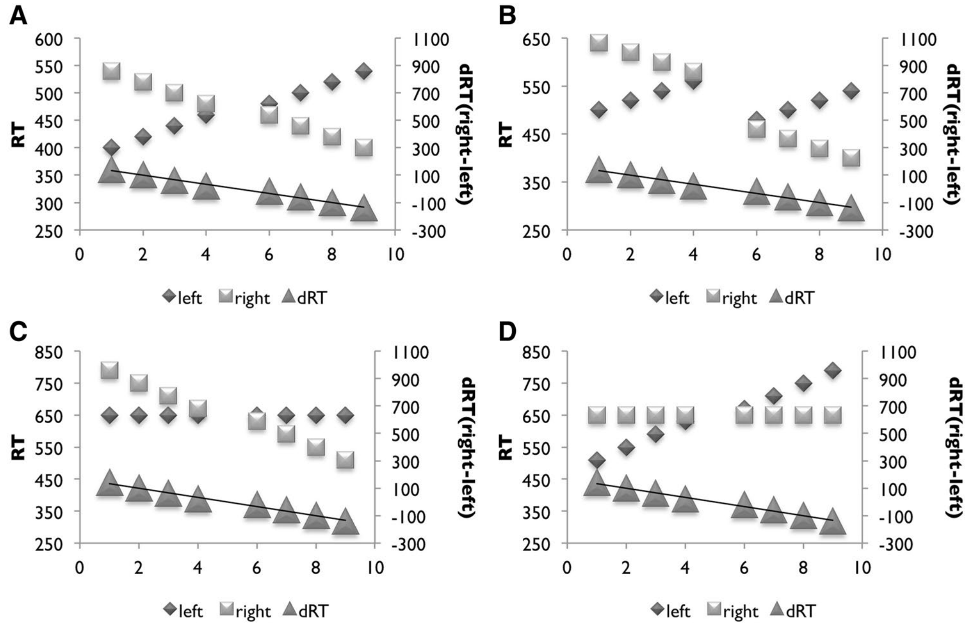

Fig. 1 Examples of different RTs data patterns (a not exhaustive list) that give rise to an identically sized PJ-SNARC effect. **a** Symmetrical pattern of left- and right-hand RTs as a function of number magnitude. **b** Increment of both left- and right-hand RTs to small relative to large number magnitudes. **c** Markedly biased increase of right-hand responses to small number magnitudes with no difference in left-hand RTs as a function of numerical magnitude. **d** Markedly biased increase of left-hand RTs to large number magnitudes with no difference in right-hand RTs as a function of numerical magnitude. The left vertical axis indicates left- and right-hand RTs, whereas the right vertical axis depicts the difference between right- and left-hand RTs (dRT). Positive values refer to conditions where left-hand responses are faster than right-hand ones. The SNARC effect typically originates from a linear decrease in dRT with increasing magnitude. In the figure, this linear decrease is represented by the black regression line: the line slope reflects the strength of the SNARC effect. Note that in all scenarios/panels the regression line has an identical slope

expresses the size of the SNARC. Although powerful in expressing the size, this approach does not capture other crucial aspects in the distribution of RTs that give rise to the SNARC. This is because an identical SNARC can arise from very different modulations of left-side and right-side RTs. Figure 1 illustrates this phenomenon by showing that compared to the normal pattern (i.e. a symmetrical increment of left-side RTs and decrement of right-side RTs as a function of number magnitude; Fig. 1a), an identical regression weight, i.e. an identical SNARC effect, can also result from (non-exhaustive list): (a) a general and response side independent increase in RTs to small number magnitudes (Fig. 1b); (b) pathological slowing of right-side RTs to small numbers, relative to large numbers, and a concomitant loss of the relationship between left-side RTs and number magnitude (Fig. 1c); (c) a pathological slowing of left-side responses to large numbers, relative to small ones, and a concomitant loss of the relationship between right-side RTs and number magnitude (Fig. 1d). These examples point out the importance of investigating the RTs patterns to draw final conclusions on whether PJ and MC are equally affected in spatial neglect or not.

On this ground, we tested whether the data-patterns underlying the PJ and MC SNARC effects in neglect patients differ from that of RBD patients without neglect and healthy controls. By investigating and comparing the performance of the same RBD patients in PJ and MC SNARC tasks, we focused more directly on the possible differences between the spatial coding of numbers adopted in these two tasks. The presence of abnormal lateral spatial biases in both tasks would suggest a single modality for the spatial representation of number magnitudes (as assumed by the mental number line account). In contrast, the presence of abnormal RTs asymmetries in the response to numbers 4 and 6 that are adjacent to the numerical reference 5 in the MC task and the presence of normal left-side increase and right-side decrease in RTs as a function of number magnitude in the PJ task would proof, at the same time, that spatial effects are present in both tasks though the MC effect is disturbed while the PJ is not. This dissociation would suggest the existence of multiple spatial representations of the same number magnitudes.

Participants

Twenty-one patients suffering from right brain damage, confirmed by CT or MRI scan, were recruited from two different rehabilitation hospitals and from the neurological department of a university hospital. In addition, a control group of 12 healthy participants, matched with the patients for age and educational level, was also tested (4 males; average age: 69 years; SD 12; average education: 13.17 years; SD 4.53). At the moment of experimental testing, neglect was evaluated with the line bisection and the multiple item bells cancellation task (see below). These two tasks have been validated in large samples of participants (Azouvi et al. 2002; Rorden and Karnath 2010) and provide an index of different attentional abilities, i.e. parallel distribution of attention in the line bisection task and serial distribution of attention in multiple item cancellation (Binder et al. 1992; Gainotti et al. 2009). In addition, fMRI and lesion-based evidence demonstrate that these two tasks provide information about the functioning of different sectors of the parietal–frontal network that allows the deployment of attention in space (parietal areas in line bisection and frontal areas in multiple item cancellation; Binder et al. 1992; Fink et al. 2000; Verdon et al. 2009). For a patient to be assigned to the neglect group, signs of neglect had to be present in at least one of the two screening tasks. In this way, 13 neglect patients (4 females; average age: 66.15 years; SD 14.06; average education: 12.15 years; SD 5.60) and 8 patients without neglect (3 females; average age: 62.75 years: SD 10.11; average education: 12.13 years; SD 2.36) were identified. Among the neglect patients, seven patients displayed neglect only in line bisection and one patient only in the bell cancellation tasks, while the remaining five patients had neglect in both tasks. All control patients without neglect showed no sign of neglect in both screening tasks. The local ethical committee approved the study and an informed consent was signed before participation. Demographic, clinical and psychometric data of the patients are reported in Table 1.

Methods

Neglect assessment

Line bisection

Fifteen horizontal lines of three different lengths (2, 10 and 20 cm; line thickness 2.5 mm) were presented one by one, centered on a landscape A4 paper. The instructions were to mark the midpoint of these lines with a pen. Lines of the same length were presented in separate blocks, presented at different moments in the experimental session. All lines were aligned to the body midline and moving the test sheet was not permitted. No time constraints were imposed. The cut-off score for neglect on line bisection was taken from normative data collected in a sample of 206 patients with right brain damage by Azouvi et al. (2002; cut-off 20 cm lines = 6.5 mm).

Bell cancellation

Subjects were asked to search for 35 targets (bell-formed shapes) presented on a landscape A4 paper along with 280 distracters (Gauthier et al. 1989). The middle of the paper was aligned to the body midline and moving the test sheet was not permitted. No time constraints were imposed. One patient cancelled out the hammer-formed objects instead of the bells. For each participant the Centre of Cancellation was calculated (Rorden and Karnath 2010) and the cut-off score (> 0.081) reported in this study was used.

Parity judgment and magnitude comparison tasks

Digits ranging from 1 to 9 (except 5) had to be judged on the basis of their parity (odd or even) or magnitude (smaller or larger than 5) status. Both tasks consisted of two blocks differing in response mapping (odd-left and even-right or vice versa; small-left and large-right or vice versa). Each digit was presented 12 times for each response mapping condition. A trial started with the presentation of a fixation point (#; 700 ms), followed by the target number that remained on the screen until a response was given. Responses with reaction times (RTs) below 10,000 ms were considered as valid. The target numbers were presented in random order at the center of the computer screen. Viewing distance was approximately 60 cm. Stimuli ($1° \times 1.4°$) were presented in white against a black background. Each response-mapping block was preceded by eight exercise trials (each number presented once). Thirty-two subjects used the mouse as response interface and were asked to press the left button with their right index finger and the right button with the right middle finger. One neglect patient used a joystick. The mouse or joystick was aligned to the middle of the computer screen, and the left side of the screen was aligned to the body midline of the patient (see also Priftis et al. 2006). Instructions were to respond as fast and accurate as possible by pressing the left-sided or right-sided response button. Both tasks made part of a larger test battery reported elsewhere (van Dijck et al. 2012), in which task order was counterbalanced across participants. 19 participants started with the small (even)/left, large (odd)/right response mapping, and 17 participants completed PJ first[1].

[1] Tasks order and the order of the response mapping had no influence on the results. This was evaluated with different ANOVA's with both SNARC effects and the asymmetry index of the distance effect as dependent variables and Task order, Response mapping and Group membership as independent variables. All main effects and interaction effects with Task Order and Response mapping were not significant (all p's ≥ 0.10).

Table 1 Demographic and clinical information of right brain damaged patients with and without spatial neglect

	Group	Sex	Age (years)	Education (years)*	Type lesion	Location	Duration lesion (months)	Left plegia/paresis	Line bisection (20 cm) cut off: 6.5% (%)	Bell cancellation cut off: CoC > 0.081
1	Neglect patients	M	73	6	Ischemic	F–T–P	2.5	+	13.80	0.85
2		M	64	24	Haemorrhage	F–T–P	1	+	7.80	0.14
3		M	80	16	Ischemic	MCA	3.5	+	12.70	0.02
4		M	77	8	Ischemic	Basal ganglia	5.5	+	2.80	0.15
5		M	75	6	Ischemic	F–P–internal capsule	2	+	10.70	0.3
6		F	53	12	Haemorrhage	F–T–P (incl. ventricles)	27.5	±	12.70	0.26
7		M	67	6	Ischemic	subcortical	9	+	11.10	0.03
8		M	63	6	Ischemic	MCA-putamen	2	+	8.90	−0.03
9		M	67	17	Ischemic	T–P–lenticular capsule	2	+	7.80	0.14
10		M	36	17	Ischemic	Sylvain artery	1	+	7.14	0
11		F	45	14	Haemorrhage	F-Insula	2	−	12.20	0.04
12		F	82	13	na	P-O	2	+	8.80	−0.03
13		F	78	13	na	na	1	−	9.00	0
1	Patients without neglect	M	72	15	Ischemic	P	1	±	0.28	0
2		M	64	12	Ischemic	MCA	1.5	+	3.60	0.01
3		F	64	12	Ischemic	MCA-Corona radiata	9	+	−3.30	0
4		F	59	8	Ischemic	Pontine	1	±	−6.10	−0.03
5		M	75	12	Ischemic	NA	2	+	−2.00	0.03
6		F	42	15	Ischemic	T–P	2	±	−4.60	0
7		M	67	10	Ischemic	NA	1	±	−0.30	0
8		M	59	13	Ischemic	F–T	2	+	1.20	0.058

M male, *F* female; + plegia, ± paresis, − no motor deficits, *T* temporal, *P* parietal, *O* occipital, *F* frontal, *MCA* middle cerebral artery

*Counted from the first year of primary school (age 6)

Results

Neglect assessment

Line bisection

The response bias was determined by measuring the distance of the subjective midpoint from the actual midpoint. Distances were measured from the left side of the line with 0.5 mm accuracy. Only deviation scores of the 20 cm lines were considered. A rightward deviation from the midpoint of more than 6.5 mm (i.e. 6.5%) is considered as an indication for the presence of neglect (Azouvi et al. 2002). The deviation scores of the individual patients can be found in Table 1. None of the healthy controls deviated more than 3.1 mm.

Bell cancellation

The cancellation bias was calculated using the Centre of Cancellation (CoC) program (Rorden and Karnath 2010). By indicating the cancelled targets, the program provides an asymmetry index between + 1 and − 1. The more items on the left are missed, the more positive this value becomes. To evaluate whether the CoC of a patient is deviant, the cut-off score reported in Rorden and Karnath (2010) was used (CoC > 0.081). The CoC values of the individual patients can be found in Table 1. The CoC of none of the healthy controls exceeded this value (all CoC's < 0.026).

Investigations of number–space

The aim of these analyses was twofold: (1) providing a more detailed analysis of the SNARC effect and (2) providing evidence for the existence of multiple spatial codes. The result section is organized accordingly.

Detailed analyses of the SNARC effect

The analyses of the SNARC effect are reported separately for the MC and PJ. First, the size of the SNARC effect is evaluated in three incremental steps. Subsequently, the RT pattern of left and right sided responses are analyzed in detail.

For the evaluation of the size, the data were first submitted to a repeated measures ANOVA's with Group (3 levels: neglect, control patients, and healthy controls) as between-subject variable and Magnitude (8 levels: 1–4 and 6–9) and Response (2 levels: left and right) as within-subject variables. This analysis was performed to highlight the presence of an association between numbers and space (which is not necessarily linear in nature), and whether there are group differences. In this context, a significant interaction between Magnitude and Response reflects an association between numbers and space. A significant three-way interaction (with Group as an additional factor) indicates the existence of group differences in this association. (2) Importantly, as the SNARC effect reflects a linear relation between magnitude and space, this repeated measures ANOVA is complemented with a linear regression analysis (Fias et al. 1996). More precisely, dRTs (average RT right response − average RT left response) were computed for each number separately. Per subject, these dRTs were entered in a regression analysis with Magnitude as predictor. The unstandardized regression slope of the Magnitude predictor expresses the size of the SNARC effect. With this approach, a regular SNARC effect has a slope with a negative value. Subsequently, the obtained slopes were tested against zero (with a simple *t*-test) for each group separately to evaluate the presence of a SNARC effect. (3) Finally, group differences in these slopes were evaluated using one-way ANOVA. In case of significance, LSD-corrected (for multiple testing) post-hoc tests were conducted for the comparison between groups.

For the in-depth analyses of the RT pattern underlying the SNARC effect, the data of left and right sided responses were submitted to separate Group by Magnitude repeated measures ANOVA's. A significant two-way interaction indicates group differences in left or right responses to the numbers. To flesh out this interaction (in case of significance), the RT's for each number were entered in a regression analysis with Magnitude as predictor. Subsequently, these slopes were entered in a one-way ANOVA to check for possible group differences. In case of significance, LSD-corrected (for multiple testing) post-hoc tests were conducted for the comparison between groups.

Only correct responses and RT's larger than 150 ms and smaller than the individual 2SD from the average RT were included in the analyses. These trimming parameters resulted in reliable effects. The split-half reliability (with Spearman–Brown correction) was 0.92 and 0.71 for the MC SNARC and PJ SNARC, respectively. Finally, no speed–accuracy trade off was found in any of the tasks as the correlations between average RTs and the % of selected trials were negative [MC: $r(32) = -0.53$, $p = 0.002$; PJ: $r(32) = -0.27$, $p = 0.14$). When the sphericity assumption was violated, Greenhouse–Gasser correction was applied.

Parity judgement: SNARC effect Given the inclusion criteria, 89.30% (SD 5.51%), 91.28% (SD 5.90%) and 93.53% (SD 4.79%) of the trials were included for the neglect group, the control patients and the healthy controls. The Group by Magnitude by Response repeated measures ANOVA revealed main effects of Group [$F(2,30) = 10.07$, $p < 0.001$, $\eta_p^2 = 0.40$] and Magnitude [$F(2.88,107.48) = 3.05$, $p = 0.035$, $\eta_p^2 = 0.09$]. The overall average RT's were

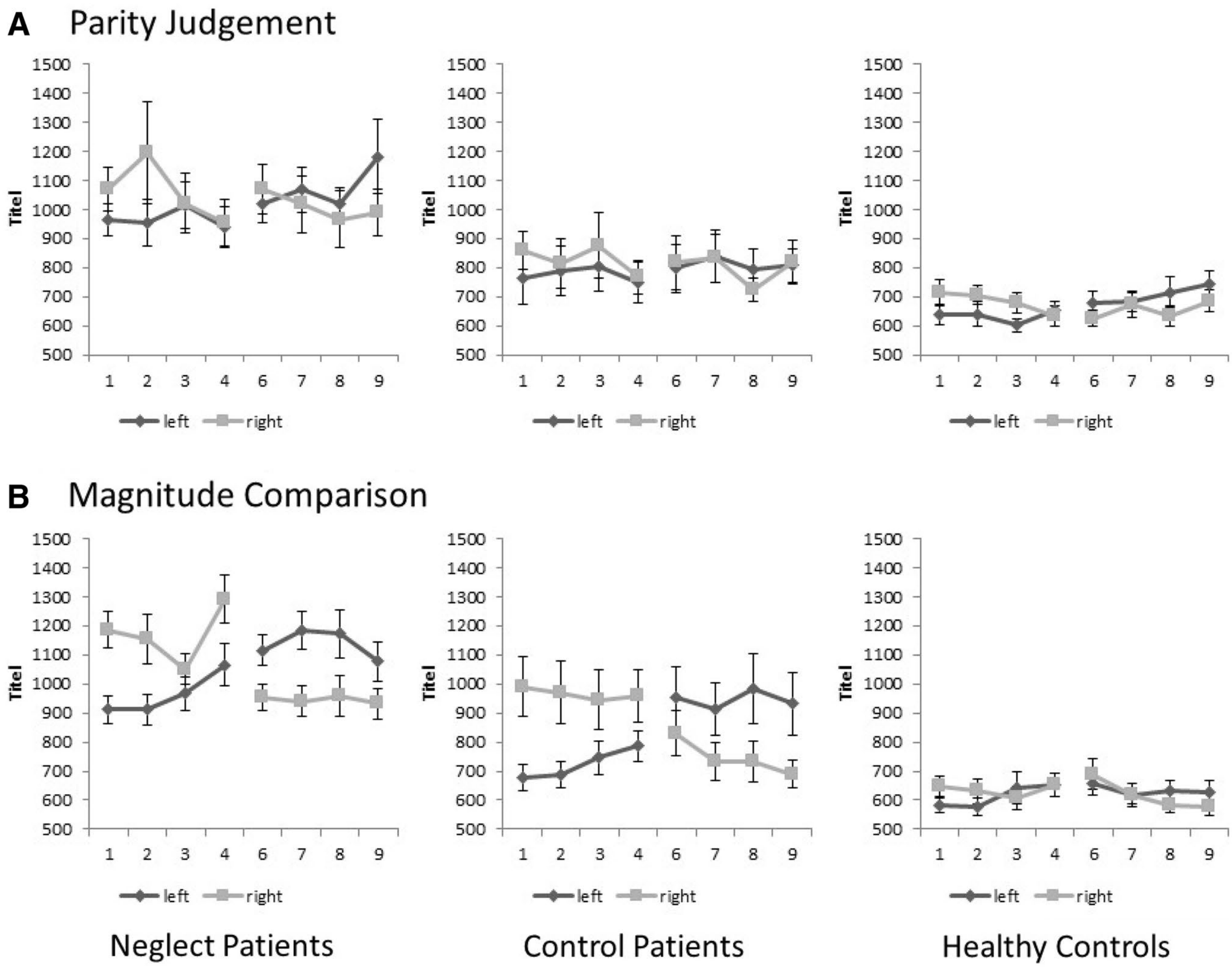

Fig. 2 Left- and right-hand RTs to numbers 1–4 and 6–9 in neglect patients, patients without neglect and healthy controls. **a** Parity Judgment task. **b** Magnitude comparison task. The error bars depict standard errors

1025 ms (SD 256 ms), 802 ms (SD 216 ms) and 667 ms (SD 107 ms) for the neglect patients, the control patients and the healthy controls. Post-hoc tests showed that the RT of the control groups did not differ from each other ($p > 0.156$), while the neglect group did (both p's < 0.020). The RT for each number was 838, 849, 827, 788, 839, 853, 820 and 880 ms. The interaction between Magnitude and Response was also significant [$F(3.58,107.48) = 4.24$, $p = 0.004$, $\eta_p^2 = 0.12$], reflecting a systematic association between numbers and space. The three-way interaction failed to reach significance [$F(7.17, 107.48) = 1.28$, $p = 0.266$, $\eta_p^2 = 0.08$] suggesting that there were no group differences in this effect (see Fig. 2a). No other main effect or interaction effect reached significance [all F's < 1; all p's > 0.35, $\eta_p^2 < 0.06$].

The linear regression approach shows that the above-mentioned interaction between Magnitude and Response reflects a SNARC effect. The average regression weight of the neglect group was − 35.64 (SD 34.01), of the control patients − 12.91 (SD 7.85) and of the healthy controls − 20.10 (SD 13.76). In all groups, this average was different from zero [neglect: $t(12) = -3.78$, $p = 0.003$, Cohen's $D = 1.05$; control patients: $t(7) = -4.65$, $p = 0.002$, Cohen's $D = 1.64$; healthy controls: $t(11) = -5.06$, $p < 0.001$; Cohen's $D = 1.46$]. Finally, the one-way ANOVA with those regression weights as dependent and Group as independent variable failed to reach significance [$F(2,30) = 2.67$, $p = 0.085$, $\eta_p^2 = 0.15$]. Together, these analyses are suggestive for an equally sized PJ SNARC effect in all groups.

Parity judgement: left-sided responses The repeated measures ANOVA revealed a main effects of Group [$F(2,30) = 10.75$, $p < 0.001$, $\eta_p^2 = 0.42$] and Magnitude [$F(3.88,116.38) = 4.97$, $p = 0.001$, $\eta_p^2 = 0.14$] (see Fig. 2a).

Further supporting the idea that neglect doesn't impact spatial coding of numbers in parity judgment, the interaction between Group and Magnitude failed to reach significance [$F(7.76,116.38)=1.29$, $p=0.26$, $\eta_p^2=0.08$]. The average regression weight of the neglect group was 20.69 (SD 16.91), of the control patients 5.13 (SD 10.64) and of the healthy controls 14.16 (SD 10.50). A one-way ANOVA with those regression weights as dependent and group membership as independent variable was significant [$F(2, 30)=3.31$, $p=0.05$, $\eta_p^2=0.18$]. This effect is driven by the control patients showing a smaller effect than the neglect patients ($p=0.015$), while no other group differences were significant (both p's >0.15). This means that the effect of both patient groups did not differ from the healthy controls.

Parity judgement: right-sided responses The repeated measures ANOVA revealed a main effects of Group [$F(2,30)=8.99$, $p=0.001$, $\eta_p^2=0.37$] and Magnitude [$F(2.65, 79.51)=2.91$, $p=0.046$, $\eta_p^2=0.09$] (see Fig. 2a). Further supporting the idea that neglect doesn't impact spatial coding of numbers in parity judgment, the interaction between Group and Magnitude failed to reach significance [$F(5.30,79.51)=0.97$, $p=0.446$, $\eta_p^2=0.06$]. The average regression weight of the neglect group was −14.95 (SD 20.27), of the control patients −7.78 (SD 7.69) and of the healthy controls −5.93 (SD 9.17). A one-way ANOVA with those regression weights as dependent and group membership as independent variable failed to reach significance [$F(2,30)=1.33$, $p=0.28$, $\eta_p^2=0.08$].

Magnitude comparison: SNARC effect Given the inclusion criteria, 88.02% (SD 5.55%), 89.45% (SD 5.78%) and 96.35% (SD 1.94%) of the trials were included for the neglect group, the control patients and the healthy controls. For one neglect patient, only responses from one response mapping were collected. For this reason, the data of this patient were discarded from the SNARC analyses.

The repeated measures ANOVA revealed main effects of Group [$F(2,29)=21.64$, $p<0.001$, $\eta_p^2=0.60$] and Magnitude [$F(7,203)=5.40$, $p<0.001$, $\eta_p^2=0.16$]. The overall average RT's were 1025 (SD 163 ms), 832 (SD 215 ms) and 623 ms (SD 117 ms) for the neglect patients, the control patients and the healthy controls. Post-hoc tests demonstrated that all groups differ from each other (all p's <0.008). The RT for each number was, 808, 798, 815, 885, 855, 825, 824 and 793 ms. Both the two-way interactions between Group × Magnitude [$F(14,203)=1.98$, $p=0.021$, $\eta_p^2=0.12$] and Magnitude × Response [$F(2.57,74.40)=19.88$, $p<0.001$, $\eta_p^2=0.41$] were significant. The interaction between Group and Magnitude suggests the asymmetry of the distance effect, which is most strongly present in the neglect group (see below for a more detailed analysis) while the interaction between Magnitude and Response reflects a systematic association between numbers and space. Finally, the three-way interaction between Group, Magnitude and Response reached significance [$F(5.13,74.40)=4.05$, $p=0.002$, $\eta_p^2=0.22$], suggesting that the association between numbers and space is different between groups.

The linear regression approach shows that the above-mentioned interaction between Magnitude and Response reflects a SNARC effect. The average regression weight of the neglect group was −63.68 (SD 60.81), of the control patients −81.01 (SD 52.24) and of the healthy controls −10.95 (SD 21.85). All slopes (marginally) differed from zero [neglect patients: $t(11)=-3.63$, $p=0.004$, Cohen's $D=1.05$; control patients: $t(7)=-4.39$, $p=0.003$, Cohen's $D=1.55$; healthy controls: $t(11)=-1.74$, $p=0.055$ (one-sided), Cohen's $D=0.48$]. The one-way ANOVA with those weights as dependent variable and Group as independent variable was significant [$F(2,29)=6.28$, $p=0.005$, $\eta_p^2=0.30$]. Post-hoc analyses demonstrate that the SNARC of both patient groups do not differ from each other ($p=0.429$) while the SNARC of both neglect patients and control patients differed from the healthy controls. (neglect: $p=0.011$; control patients: $p=0.003$). Together, these findings point to an equally enlarged MC SNARC effect in both patient groups.

Magnitude comparison: left-sided responses The repeated measures ANOVA revealed a main effects of Group [$F(2,29)=20.71$, $p<0.001$, $\eta_p^2=0.59$] and Magnitude [$F(3.34,97.00)=14.43$, $p<0.001$, $\eta_p^2=0.33$] (see Fig. 2B). In addition, the interaction between Group and Magnitude was also significant [$F(6.69,97.00)=2.88$, $p=0.010$, $\eta_p^2=0.17$].

Regression analyses confirmed this finding. The average regression weight of the neglect group was 31.06 (SD 28.20), of the control patients 39.93 (SD 32.00) and of the healthy controls 4.85 (SD 13.90). A one-way ANOVA with those regression weights as dependent and group as independent variable was significant [$F(2,29)=5.64$, $p=0.009$, $\eta_p^2=0.28$]. Post-hoc analyses showed that the regression weights of the control patients and of the neglect group did not differ from the each other ($p=0.443$), while the weights of both neglect patients and control patients differed from the healthy controls. (neglect: $p=0.015$; control patients: $p=0.004$].

Magnitude comparison: right-sided responses The repeated measures ANOVA revealed a main effects of Group [$F(2,29)=21.63$, $p<0.001$, $\eta_p^2=0.60$] and Magnitude [$F(3.62,105.084)=15.22$, $p<0.001$, $\eta_p^2=0.34$] (see Fig. 2b). In addition, the interaction between Group and Magnitude reached significance [$F(7.24,105.04)=3.74$, $p=0.001$, $\eta_p^2=0.21$].

Regression analysis confirmed this finding. The average regression weight of the neglect group was − 32.62 (SD 36.03), of the control patients − 41.08 (SD 21.83) and of the healthy controls − 6.10 (SD 12.34). A one-way ANOVA with those regression weights as dependent and group as independent variable was significant [$F(2,29)=5.30$, $p=0.011$, $\eta_p^2=0.27$]. Post-hoc analyses showed that the regression weights of the healthy controls differed from both patient groups [neglect: $p=0.018$; control patients: $p=0.004$] while the comparison of two patient groups was not significant ($p=0.478$).

Investigating the existence of multiple spatial codes

Taken together, the results reported above suggest that the PJ SNARC and MC SNARC draw upon different spatial codes. To provide further evidence for this idea, two additional analyses were conducted. First, the data of the MC task were further analyzed to investigate group differences in the distance effect. Second, correlational analyses were performed with the size of the SNARC effects obtained from both tasks and the size of the asymmetry of the distance effect to verify whether they draw upon the same or different spatial codes.

The evaluation of the distance effect started with a repeated measures ANOVA with Distance (4 levels: 1–4) and Magnitude (2 levels: small and large) as within-subject variables and Group (3 levels: Neglect, Control patients, and Healthy controls) as between subject variable. In this analysis, the three-way interaction is indicative for group differences in the distance effect. To flesh out this interaction, the asymmetry of the distance effect was determined for each subject by calculating an asymmetry index with the following formula: (average RT number 4 − average RT number 1) − (average RT number 6 − average RT number 9). A positive value obtained with this formula indicates that the distance effect for small numbers is larger than for large numbers. For each group, it was verified whether this asymmetry index significantly differed from zero (with a one sample *t*-test) and whether group differences existed with a one-way ANOVA. In case of significance, LSD-corrected (for multiple testing) post-hoc tests were conducted for the comparison between groups.

Asymmetry of the magnitude comparison distance-effect

To investigate the presence of a potential asymmetry in the distance-effect, average RT's were computed for each number separately and submitted to repeated measures ANOVA with Magnitude (two levels: smaller and larger than 5) and Distance from the referent (four levels) as within-subject and Group as between-subject variables. This analysis revealed a main effect of Group [$F(2,30)=19.15$, $p<0.001$, $\eta_p^2=0.56$] and a main effect of Distance [$F(3,90)=12.51$, $p<0.001$, $\eta_p^2=0.29$]. Slower responses were given by the neglect patients (1025 ms; SD 163 ms) than by the patients without neglect (832 ms; SD 215 ms) and the healthy controls (623 ms; SD 117). Average RT from distance 4 to distance 1 was 801, 816, 821, and 871 ms. A polynomial contrast confirmed a linear trend [$F(1,30)=35.35$, $p<0.001$, $\eta_p^2=0.54$], indicating the presence of a distance-effect. In addition, a triple interaction [$F(6,90)=4.04$, $p=0.003$, $\eta_p^2=0.21$] between Magnitude, Distance and Group was observed. A visual inspection of Fig. 2b suggests that this triple interaction reflects an asymmetry in the distance effect, which is most strongly present in the neglect group. To get statistical support for this interpretation, the asymmetry index (see above for the formula) was calculated. The average asymmetry index of the neglect group was 114.68 (SD 156.07), of the control patients − 51.45 (SD 165.22), and of the healthy controls − 35.80 (SD 44.21). For the neglect group the asymmetry index was significantly different from zero [$t(12)=2.64$, $p=0.021$, Cohens's $D=0.73$]. For the healthy controls the asymmetry index was also significant [$t(11)=-2.81$, $p=0.017$, Cohens's $D=0.81$], but in the reversed direction as the neglect patients. For the control patients, this index was not significant [$t(7)=-0.51$, $p=0.411$, Cohens's $D=0.31$]. The one-way ANOVA with those indexes as dependent and Group as independent variable was significant [$F(2,30)=5.77$, $p=0.008$, $\eta_p^2=0.28$]. Post hoc analyses demonstrate that the asymmetry index of the neglect group is significantly different from both control groups (both p's <0.009) and that no difference was observed between the healthy controls and the control patients without neglect ($p=0.798$).

Correlations

In the PJ the spatial coding of numbers seems unaffected by neglect or brain damage in general. In contrast, the MC SNARC effect is enlarged in both patient groups. The only effect that is selectively affected by neglect is the distance effect. To further substantiate the hypothesis that these findings reflect the existence of different spatial codes associated with numbers, correlations were calculated between the regression weights associated with the size of both SNARC effects and the index of the asymmetry of the distance effect. If all effects have their origin in the same underlying mental representation, they should be highly positively correlated with each other. The existence of multiple spatial codes will be reflected in the absence of such correlation. Since not all variables were normally distributed, the Spearman correlations were calculated. Further strengthening the idea of the existence of multiple spatial codes associated to numbers, correlations were between $r = -0.09$ and 0.13 with all $p' > 0.480$[2]. It is important to note that with a sample size of 33, an (2-sided) α level of 0.050 and power of 0.80, a correlation larger than $r = 0.470$ becomes significant. It is reasonable to expect such high correlations when all the effects have their origin in the same underlying spatial mental representation.

Discussion

The aim of the current study was twofold: (1) to investigate whether the PJ and MC SNARC effects that were previously found in neglect patients originates from normal RTs patterns; (2) to explore whether different left/right spatial codes can be associated to numbers by comparing the spatial features of the PJ and MC task. The results demonstrate that neglect patients show a PJ SNARC that is normal in size and arises from reaction time (RT) patterns that are comparable to those found in patients without neglect and healthy controls. This latter observation provides the so far missing evidence that the relation between numbers and space in the PJ is insensitive to the spatial-attentional deficits associated with neglect. In MC on the contrary, neglect patients suffered from a pathological spatial bias in their distance effect, while their MC SNARC effect was not (quantitatively or qualitatively) modulated by neglect. These dissociations are difficult to reconcile with the idea that neglect impacts the explicit processing but not the implicit processing of numerical magnitude (e.g. Priftis et al. 2006) and suggest that multiple left/right spatial codes are associated to the same number magnitudes, even within the same task. This conclusion was further supported by the absence of any correlation between the PJ SNARC, MC SNARC and the asymmetry of the distance effect.

Usually, number–space interactions are attributed to the mental representation of numbers taking the shape of a mental number line, with small numbers on the left and large numbers on the right. Different hypotheses were advanced to identify the functional origin of the spatial mental number line (for review see Aiello et al. 2012; Fattorini et al. 2016; Rossetti et al. 2011; van Dijck et al. 2015). The oldest hypothesis holds that spatial codes are an inherent part of number semantic meaning (Fischer et al. 2003; Hubbard et al. 2005). As such, from the moment a number is processed, its corresponding location on the mental number line is automatically triggered and this independently from the task at hand. Spatial numerical associations are explained by assuming that the activation of this spatial code biases response selection and/or spatial attention. Therefore, spatial deficits giving rise to a bias in the perceptual and/or mental representation of space, are expected to bias number processing as well. A second interpretation is that the left/right coding of numbers depends on culturally acquired association between "left/right" and "small/large" semantic codes, with left/small sharing a negative semantic polarity and large/right a positive one (Proctor and Cho 2006). A third hypothesis is that it is the use of left/right spatial codes in the task at hand that determines a corresponding mental spatialization of number magnitudes (Fattorini et al. 2015). The results of the present study show that, independently from the interpretation of the functional origin of the mental number line, the cognitive architecture behind the number–space interactions is more complex than initially thought, and that multiple left-to-right spatial mappings can be associated with numbers (instead of one as assumed in the hypotheses mentioned above). The fact that even in a task that requires the use of left/right spatial response codes, the spatial RTs patterns that give rise to the normal-sized PJ SNARC are not influenced by spatial neglect is at odd with the idea that the MC and PJ tasks are grounded on the same spatially organized mental number line. Therefore, the findings of the current study support the idea that different spatial maps of numbers co-exist.

How can the same number magnitude be related to different left/right representations in mental space? With respect to the dissociation between the normal distribution of RTs in the PJ task and the asymmetrical distance effect in the MC task, a number of hypotheses can be advanced. Number magnitudes convey both cardinal-magnitude and ordinal-rank information (Jacob and Nieder 2008). The pattern of RTs observed in the PJ task suggests a sequential scanning of the series of numbers presented during the task, i.e. 1–9, because left-hand RTs linearly increased and right-hand RTs linearly decreased the later the number in the series. This finding suggests that during the performance of the PJ task, the position of numbers on the mental number line is recalled and inspected through a close sequential repetition of the overlearned sequence of the same numerals (e.g. the sequence 1–9 or the multiplication table of 2). In addition, this sequential repetition loads mainly on verbal memory, because dual-task interference studies have demonstrated that concurrent verbal memory task disrupts the PJ SNARC while a spatial memory load does not have an influence (van Dijck et al. 2009). Stated differently, these findings suggest that spatial neglect does not disturb the ability of associating the sequential position of an item in over-learned ordinal

[2] To ensure that these correlations were not obscured by the group differences that are present in the data, the analyses were repeated on the data of all participants together, but with all the data being normalized to *z*-scores for each subject group separately (see van Dijck et al. 2012 for a similar procedure). These analyses did again not produce significant results ($r = 0.13$ and 0.24 with all $p' > 0.193$).

sequences that depends on verbal memory with a spatial response code.

These interpretations can be further refined by considering that in patients with neglect the dissociation between the asymmetrical distance effect and the normal MC SNARC might arise at different processing steps (e.g. stimulus processing, decision processes, response selection) while performing MC. As an example, the distance effect has been related to decision processes during the comparison between the numerical target and the numerical reference (Van Opstal et al. 2008), while the SNARC is typically attributed to the phase of response selection (e.g. Gevers et al. 2006). Therefore, it is possible to hypothesize that independent spatial representations are generated to guide task performance at each of these two processing stages. If this would be the case, the current results suggest that neglect has an impact on the spatial codes used in the MC decision process, while it does not affect the use of spatial codes for response selection. Interestingly, this idea not only explains why two different spatial codes can be related to the same stimulus, but also why one code is sensitive to neglect while the other is not. MC requires, by definition, coding the magnitude of one number in reference to the magnitude of another one. This requires, in turn, a coordinate processing of numerical magnitude. In contrast, mapping the outcome of a MC or a PJ on a binary left/right response code requires only binary/categorical processing. It is well known that space can be processed both along a coordinate and/or a categorical dimension (Kosslyn 1987) and that coordinate coding mainly draws upon the right hemisphere while categorical coding mainly draws upon the left one (Jager and Postma 2003). Within this framework, spared MC and PJ SNARC effects in neglect patients can be attributed to their reliance on the intact left hemisphere while the biased distance effect in MC can be attributed to impaired processing in the damaged right hemisphere. This idea comes close to recent proposals that both in the case of MC and PJ tasks, the SNARC effect originates (primarily) from the congruency between the concepts small/large and left/right (e.g. Gevers et al. 2010). Within this context, the SNARC effect is believed to be verbal–spatial (in contrast to visuo-spatial) in nature.

Finally, it is possible that the need for working memory is underlying the differential effect of neglect on the SNARC and distance effect. Evidence exists that both the PJ and MC SNARC depend on the availability of working memory resources, while for the distance effect this is not the case. For example, van Dijck et al. (2009) showed that the PJ SNARC disappears when measured during the retention interval of a verbal working memory task and that the MC SNARC disappears when visuo-spatial working memory resources were unavailable. This observation in MC was a replication of an earlier study which also showed that the distance effect was not affected by a working memory load (Herrera et al. 2008). Follow up studies confirm that the SNARC effect depends on temporary bindings made in working memory (see Fias and van Dijck 2016 and; Abrahamse et al. 2016 for recent accounts). In the current context, it is thus possible that neglect only impairs effects/processes that draw upon more long-term representations. Additional work will be needed to further clarify the role between ordinal coding in working memory and neglect, as recent evidence suggests that in verbal working memory the serial order of the items are also mentally organized in space according to our reading habits (begin items are associated with left and end items with right in people who read from left to right; for reviews see Abrahamse et al. 2014, 2017). In this context, it is interesting to note that neglect patients have general difficulties in maintaining verbal information in correct serial order in mind (without spatial biases), a deficit that is associated with their neglect severity (Antoine et al. 2018).

Another outstanding question is why the PJ SNARC remained equal in size, while the MC SNARC was enlarged both in patients with and without neglect, as compared to controls. At first sight, this observation further supports previous claims that the SNARC effects of both tasks are reflections of different spatial codes. Based on the dual task studies just mentioned, it was concluded that the spatial coding of numbers underlying the PJ SNARC is verbal–spatial in nature, while the coding underlying the MC SNARC is visuo-spatial in nature (van Dijck et al. 2009). While this interpretation provides a potential explanation to why the PJ SNARC is unaffected by neglect, a reduction (rather than an enlargement) of the MC SNARC would be predicted in the neglect group. How can we reconcile then these seemingly inconsistent findings? In healthy subjects, an enlargement of congruency effects (like the SNARC effect) can easily be elicited by imposing a proper additional cognitive load to interfere with executive control (Lavie et al. 2004). On the other hand, congruency effects disappear when working memory resources, needed to generate the necessary underlying mental representation, are depleted (e.g. van Dijck et al. 2009). The enlarged MC SNARC in our patient sample suggests that enough resources were available to build up the mental representation, but that both patient groups suffered from a reduction of executive control. Interestingly, in healthy subjects, an enlargement of congruency effects only occurs when the nature of the cognitive load overlaps with the nature of the congruency effect (Kim et al. 2005). The fact that the PJ SNARC is unaffected in patients while the MC SNARC enlarges, provides thus further (indirect) support for the different nature of the spatial codes involved in the SNARC effect of both tasks.

In conclusion, the results of the present study demonstrate that the tight relationship between numbers and space is much more complex than previously thought: even within the same task, multiple spatial codes exist that can be differentially associated to numbers. Current theories and models should, therefore, be extended to incorporate these novel findings. Future empirical and modelling work is needed to understand the details of the different left-to-right spatial representations of number magnitudes and the cognitive mechanisms that contribute to their formation.

Acknowledgements We would like to thank Mario Pinto and Michelle Pellegrino for their help in testing additional patients.

References

Abrahamse E, van Dijck J-P, Majerus S, Fias W (2014) Finding the answer in space: the mental whiteboard hypothesis on serial order in working memory. Front Hum Neurosci 8:932. https://doi.org/10.3389/fnhum.2014.00932

Abrahamse E, van Dijck JP, Fias W (2016) How does working memory enable number-induced spatial biases? Front Psychol 7:977

Abrahamse EL, van Dijck JP, Fias W (2017) Grounding verbal working memory: the case of serial order. Curr Dir Psychol Sci 26(5):429–433

Aiello M, Jacquin-Courtois S, Merola S, Ottaviani T, Tomaiuolo F, Bueti D, Doricchi F (2012) No inherent left and right side in human 'mental number line': evidence from right brain damage. Brain 135(8):2492–2505

Antoine S, Ranzini M, Dijck JP, Slama H, Bonato M, Tousch A et al (2018) Hemispatialneglect and serial order in verbal working memory. J Neuropsychol. https://doi.org/10.1111/jnp.12145

Azouvi P, Samuel C, Louis-Dreyfus A, Bernati T, Bartolomeo P, Beis JM, De Montety G (2002) Sensitivity of clinical and behavioural tests of spatial neglect after right hemisphere stroke. J Neurol Neurosurg Psychiatry 73(2):160–166

Berti A, Rizzolatti G (1992) Visual processing without awareness: evidence from unilateral neglect. J Cogn Neurosci 4(4):345–351

Binder J, Marshall R, Lazar R, Benjamin J, Mohr JP (1992) Distinct syndromes of hemineglect. Arch Neurol 49(11):1187–1194

Dehaene S (1997) The number sense: how the mind creates mathematics. Oxford University Press, New York

Dehaene S, Bossini S, Giraux P (1993) The mental representation of parity and number magnitude. J Exp Psychol Gen 122(3):371–396

Doricchi F, Incoccia C, Galati G (1997) Influence of figure-ground contrast on the implicit and explicit processing of line drawings in patients with left unilateral neglect. Cogn Neuropsychol 14(4):573–594

Fattorini E, Pinto M, Rotondaro F, Doricchi F (2015) Perceiving numbers does not cause automatic shifts of spatial attention. Cortex 73:298–316

Fattorini E, Pinto M, Merola S, D' Onofrio M, Doricchi F (2016) On the instability and constraints of the interaction between number representation and spatial attention in healthy humans: a concise review of the literature and new experimental evidence. Prog Brain Res 227:223–256

Fias W, Fischer MH (2005) Spatial representation of number. In: Campbell JID (ed) Handbook of mathematical cognition. Psychology Press, Hove, pp 43–54

Fias W, van Dijck J-P (2016) The temporary nature of number—space interactions. Can J Exp Psychol 70(1):33–40

Fias W, Brysbaert M, Geypens F, d'Ydewalle G (1996) The importance of magnitude information in numerical processing: evidence from the SNARC effect. Math Cogn 2(1):95–110

Fink GR, Marshall JC, Shah NJ, Weiss PH, Halligan PW, Grosse-Ruyken M, Freund HJ (2000) Line bisection judgments implicate right parietal cortex and cerebellum as assessed by fMRI. Neurology 54(6):1324–1331

Fischer MH, Castel AD, Dodd MD, Pratt J (2003) Perceiving numbers causes spatial shifts of attention. Nat Neurosci 6(6):555–556

Gainotti G, De Luca L, Figliozzi F, Doricchi F (2009) The influence of distracters, stimulus duration and hemianopia on first saccade in patients with unilateral neglect. Cortex 45(4):506–516

Gauthier L, Dehaut F, Joanette Y (1989) The bells test—A quantitative and qualitative test for visual neglect. Int J Clin Neuropsychol 11(2):49–54

Gevers W, Ratinckx E, De Baene W, Fias W (2006) Further evidence that the SNARC effect is processed along a dual-route architecture—evidence from the lateralized readiness potential. Exp Psychol 53(1):58–68

Gevers W, Santens S, Dhooge E, Chen Q, Fias W, Verguts T (2010) Verbal-spatial and visuo-spatial coding of number–space interactions. J Exp Psychol Gen 139(1):180–190

Herrera A, Macizo P, Semenza C (2008) The role of working memory in the association between number magnitude and space. Acta Psychologica 128(2):225–237

Hubbard EM, Piazza M, Pinel P, Dehaene S (2005) Interactions between number and space in parietal cortex. Nat Rev Neurosci 6(6):435–448

Jacob S, Nieder A (2008) The ABC of cardinal and ordinal number representations. Trends Cogn Sci 12(2):41–43

Jager G, Postma A (2003) On the hemispheric specialization for categorical and coordinate spatial relations: a review of the current evidence. Neuropsychologia 41(4):504–515

Kim S-Y, Kim M-S, Chun MM (2005) Concurrent working memory load can reduce distraction. Proc Natl Acad Sci USA 102(45):16524–16529

Kosslyn SM (1987) Seeing and imagining in the cerebral hemispheres—a computational approach. Psychol Rev 94(2):148–175

Lavie N, Hirst A, de Fockert JW, Viding A (2004) Load theory of selective attention and cognitive control. J Exp Psychol Gen 133(3):339–354

Lorch RF, Myers JL (1990) Regression-analyses of repeated measures data in cognitive research. J Exp Psychol Learn Mem Cogn 16(1):149–157

Marshall JC, Halligan PW (1988) Blindsight and insight in visuospatial neglect. Nature 336(6201):766

Pinto M, Fattorini E, Lasaponara S, D'Onofrio M, Fortunato G, Doricchi F (2018) Visualising numerals: a ERPs study with the attentional SNARC task. Cortex 101:1–15

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. J Cogn Neurosci 18(4):680–688

Proctor RW, Cho YS (2006) Polarity correspondence: a general principle for performance of speeded binary classification tasks. Psychol Bull 132(3):416–442

Rorden C, Karnath HO (2010) A simple measure of neglect severity. Neuropsychologia 48(9):2758–2763

Rossetti Y, Jacquin-Courtois S, Aiello M, Ishihara M, Brozzoli C, Doricchi F (2011) Neglect "around the clock": dissociating number and spatial neglect in right brain damage. In: Dehaene S, Brannon EM (eds) Space, time and number in the brain: Searching for the foundations of mathematical thought. Academic Press, Burlington, MA, pp 149–173

Schwarz W, Keus IM (2004) Moving the eyes along the mental number line: comparing SNARC effects with saccadic and manual responses. Percept Psychophys 66(4):651–664

Van Opstal F, Gevers W, De Moor W, Verguts T (2008) Dissecting the symbolic distance effect: comparison and priming effects in numerical and nonnumerical orders. Psychon Bull Rev 15(2):419–425

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

van Dijck J-P, Gevers W, Lafosse C, Fias W (2012) The heterogeneous nature of number–space interactions. Front Hum Neurosci 5:182

van Dijck JP, Ginsburg V, Girelli L, Gevers W (2015) Linking numbers to space: from thememental number line towards a hybrid account. In: Cohen Kadosh R, Dowker A (eds) The Oxford handbook of mathematical cognition. Oxford University Press, Oxford, UK, pp 89–105

Verdon V, Schwartz S, Lovblad KO, Hauert CA, Vuilleumier P (2009) Neuroanatomy of hemispatial neglect and its functional components: a study using voxel-based lesion-symptom mapping. Brain 133(3):880–894

Vuilleumier P, Ortigue S, Brugger P (2004) The number space and neglect. Cortex 40(2):399–410

Zorzi M, Bonato M, Treccani B, Scalambrin G, Marenzi R, Priftis K (2012) Neglect impairs explicit processing of the mental number line. Front Hum Neurosci 6:125