Exp Brain Res (2010) 205:479–487
DOI 10.1007/s00221-010-2383-3

RESEARCH ARTICLE

# Numbers can move our hands: a spatial representation effect in digits handwriting

**Gelsomina Perrone · Maria Dolores de Hevia · Emanuela Bricolo · Luisa Girelli**

Received: 14 January 2010 / Accepted: 23 July 2010 / Published online: 11 August 2010


**Abstract** The interaction between numbers and action-related processes is currently one of the most investigated topics in numerical cognition. The present study contributes to this line of research by investigating, for the first time, the effects of number on an overlearned complex motor plan that does not require explicit lateralised movements or strict spatial constrains: spontaneous handwriting. In particular, we investigated whether the spatial mapping of numbers interferes with the motor planning involved in writing. To this aim, participants' spontaneous handwriting of single digits (Exp. 1) and letters (Exp. 2) was recorded with a digitising tablet. We show that the writing of numbers is characterised by a spatial dislocation of the digits as a function of their magnitude, i.e., small numbers were written leftwards relative to large numbers. In contrast, the writing of letters showed a null or marginal effect with respect to their dislocation on the writing area. These findings show that the automatic mapping of numbers into space interacts with action planning by modulating specific motor parameters in spontaneous handwriting.

**Keywords** Number handwriting · Mental number line · Spatial representation · Action planning

G. Perrone · E. Bricolo · L. Girelli (✉)
Department of Psychology, University of Milano-Bicocca, Viale dell'Innovazione 10, 20126 Milan, Italy
e-mail: luisa.girelli@unimib.it

M. D. de Hevia
Department of Psychology, Harvard University, Cambridge, MA, USA

## Introduction

Current cognitive models postulate a numerical spatial representation where numbers are conceived as variable distributions of activation along a *mental number line* (Dehaene 1992; Dehaene et al. 2003). This representation has been put forward for a long time (Galton 1880) and has received early empirical support in classical studies (Moyer and Landauer 1967; Restle 1970). In particular, two semantic effects, the distance effect and the magnitude effect, characterising the performance in basic numerical tasks, have been interpreted as evidence for a representational continuum compressed towards the right. More specifically, at least in Western cultures, this spatial representation seems to be oriented along a left-to-right direction. The most convincing evidence for this hypothesis comes from the Spatial Numerical Association of Response Codes effect (SNARC), a stimulus–response association where small digits are associated with left-sided responses and large digits with right-sided responses (Dehaene et al. 1993, for a review Wood et al. 2006). Critically, the spatial orientation of the mental number line appears to correlate with the reading and writing direction (Dehaene et al. 1993; Shaki et al. 2009), although its observation with pedal responses (Schwarz and Müller 2006) suggests that this phenomenon does not simply reflect an overlearned motor association between numbers and the effectors associated with writing (i.e., hands).

More critically, the association between numerical magnitude and external space has been shown to emerge at different stages of cognitive processing and in a variety of experimental conditions. First, numbers have been reported to cause lateralised shifts of covert attention as a function of their magnitude (Fischer et al. 2003; Galfano et al. 2006; Casarotti et al. 2007; Dodd et al. 2008; Nicholls et al.

2008). Second, number magnitude influences motor outcomes during tasks requiring either oculomotor or unimanual responses: a SNARC effect has been reported with eye movements during a parity classification task, with responses to small digits initiated faster to the left and those to large digits to the right (Fischer et al. 2004), as well as with an odd–even pointing task, where centrally presented digits yielded faster movements towards the left or towards the right as a function of their magnitude (Fischer 2003). However, in both studies, movement amplitude was not modulated by number magnitude, suggesting that numerical information seems to influence motor planning rather than motor execution (Fischer 2003; Fischer et al. 2004). Furthermore, the impact of numerical information on motor planning has been strengthened by the finding of a congruity effect between spatial location of a target number and its magnitude in a Go/No Go parity judgement task with pointing as motor response (Ishihara et al. 2006). In this study, left-sided movements were initiated faster towards small digits compared to larger digits and right-sided movements were initiated faster towards large digits compared to smaller digits. Critically, this mapping seemed to occur in a continuous, rather than dichotomic, way (Ishihara et al. 2006).

Recently, a series of studies shed light on the interaction between numbers and action-related processes, reporting a systematic effect of magnitude information on grasping movements (Andres et al. 2004; Lindemann et al. 2007; Moretto and di Pellegrino 2008), on grasping estimation (Badets et al. 2007), and on prehension action judgement (Chiou et al. 2009). For example, in a parity classification task, numerical magnitude modulated the time to begin the movement: grip closure was initiated faster in response to a small digit, while grip opening was initiated faster in response to a large digit (Andres et al. 2004). This is consistent with the view that numerical values and object size exert a similar influence on motor programming because they share common representations in the dorsal visual pathway (Walsh 2003; Andres et al. 2004; Bueti and Walsh 2009).

Critically, Fischer and Miller (2008) investigated whether the influence of numerical magnitude on action extends to irrelevant parameters of the motor response, such as the relative force of a key-press response in a parity or magnitude judgement task. In both conditions, the numerical size had little or no effect on the response force parameter, suggesting that the influence of number on the initiation and selection of action (Andres et al. 2008) does not extend to action execution (Fischer and Miller 2008). In fact, relevant digits printed on visual objects influence grip aperture only in the initial phase of grasping movements, strengthening the hypothesis that number magnitude interacts with object spatial information during motor planning (Andres et al. 2008). Finally, Song and Nakayama (2008), using a lateralised manual pointing task, reported a systematic deviation of hand trajectory related to number magnitude. Subjects were required to classify central numbers by their magnitude (smaller or larger than ‘five’) by reaching a square located to the left or right, respectively. They observed that reaching trajectories were systematically shifted in position according to numerical differences between the target and the number ‘five’.

Overall, the reviewed literature supports one or the other of two phenomena. First, the automatic[1] activation of a spatial numerical representation influences the planning of lateralised movements across different conditions (i.e., eyes, pointing), suggestive of a spontaneous association between left-sided responses and small quantities, and right-sided responses and large quantities (Fischer et al. 2004; Ishihara et al. 2006). Second, the automatic processing of numerical information has an impact on planning manual gestures (Andres et al. 2004; Badets et al. 2007; Lindemann et al. 2007; Moretto and di Pellegrino 2008; Chiou et al. 2009), suggestive of a generalised magnitude code for action-related purposes, as proposed by the ATOM theory (Walsh 2003).

The present study contributes to this line of research by addressing, for the first time, the impact of magnitude information on an overlearned complex motor plan that does not require explicit lateralised movements or strict spatial constraints: spontaneous handwriting. Handwriting is a complex multi-componential motor skill that, at a first stage, requires the control of hand placement by the movement of the arm. The trajectory of this movement modulates the specific location in the writing plane where writing occurs.

Our research investigates whether the motor parameters involved in the handwriting of numbers are modulated by the numbers’ magnitude. The general question we address is whether the spatial mapping of numbers in the representational space interferes with the motor planning involved in number handwriting, determining a spatial dislocation of the written output as a function of their magnitude.

First, we hypothesised that the automatic mapping of numbers on an oriented spatial representation induces a spatial dislocation in writing, with small numbers being written more towards the left relative to large numbers.

Second, we investigated whether this phenomenon may be modulated by task requirements and, thus, by the level of processing requested. Several studies have recently shown that magnitude information influences performance

[1] In line with all the relevant literature within this context, access to numerical information has been said to be automatic by virtue of being autonomous; that is, it begins and runs to completion without intention (Zbrodoff and Logan 1986).

even (Fias et al. 1996) or more so (Priftis et al. 2006) when it is irrelevant to the task. This effect is mainly reflected in the chronometric data by the speeding up of the responses compatible with the irrelevant numbers (e.g. SNARC effect). In particular, unimanual or bimanual lateralised responses to numbers, whether relevant or irrelevant to the task, are speeded up when compatible with the relative position of the numbers along the mental number line.

To this aim, the present study investigates the effect of numerical magnitude on the action planning involved in handwriting of Arabic digits in three different tasks: simple copy, writing by dictation, and written naming. These tasks share the final executive components required in handwriting but differ in their input processing. In particular, in the simple copy task, the activation of an internal representation is not necessarily required, since the stimulus to be produced is always available (Margolin 1984). On the contrary, writing, whether by dictation or in written naming, implies the retrieval of an internal representation of the target, although the two tasks may differ in the extent to which they imply semantic mediation (Cipolotti and Butterworth 1995; Seron and Noël 1995). Our prediction was that the impact of numerical information on motor planning would be maximised when the number to be produced must be internally generated (e.g., written naming and writing to dictation), but limited or absent when the stimulus is visually available (e.g., copy from a model).

Third, we tested whether the observed spatial dislocation in number handwriting reflects an overlearned motor pattern associated with counting. Thus, stimuli in all tasks were presented in both random and ordered sequences: in the former, the stimuli sequence was randomly produced (e.g., "nine, two, four, …"), and in the latter, the stimuli consisted of the conventional counting sequence (e.g., "one, two, three, …"). If the spatial dislocation in written production is induced by the automatic activation of a spatial representation, the effect of number should appear for both ordered and random sequences.

Finally, we investigated whether other non-numerical sequences, such as the letters of the alphabet, may produce spatial dislocation effects during handwriting. Since the SNARC effect emerges with non-numerical ordinal sequences, it has been recently suggested that a spatial mental representation is not unique to magnitude information (Gevers et al. 2003, 2004; Previtali et al. 2010). However, although spatial mapping may occur for different ordered sequences, its intrinsic relevance is likely to differ for numerical, alphabetical, and other verbal sequences (e.g., months). Numbers are indeed the most overlearned and overused ordered sequence, the only sequence where order holds cardinal meaning. For this reason, we hypothesised the spatial dislocation to be systematic only in number writing.

## Experiment 1. Writing of numbers

In order to test the hypothesis that the automatic mapping of numbers on the *mental number line* may induce a spatial dislocation in writing, subjects were presented with three different tasks all requiring written production of Arabic numbers: (i) copy from a model (hereafter, copy task), (ii) writing to dictation, and (iii) written naming of numerosities. While simple copy does not require semantic processing, writing to dictation and written naming vary in their semantic requests. Although writing Arabic digits to dictation may, in principle, be accomplished bypassing semantics (Deloche and Seron 1987; Cipolotti and Butterworth 1995; Dehaene and Cohen 1995), the evidence suggests that access to magnitude information occurs automatically during transcoding (e.g. Dehaene and Akhavein 1995). Finally, in written naming, access to magnitude information is obligatory, since the task requires associating an Arabic number with a specific non-symbolic numerosity.

### Materials and methods

#### *Subjects*

Sixteen right-handed undergraduate students (8 women) from the University of Milano-Bicocca participated in this study. The mean age was 24.9 years (range 20–38). All participants had normal or corrected to normal vision and were naive to the purpose of the experiment.

#### *Apparatus*

Participants were individually tested in a quite and dark room. They sat about 45 cm away from the screen, and the centre of the digitising tablet was aligned with the mid-sagittal plane of the participant's trunk. Stimuli were presented on a white background on Samsung Sync Master 7535 Monitor (resolution of 1,024 × 768 pixels, 35.8° × 29.1°). Spontaneous writing, performed with an electromagnetic pen, was registered by means of a digitising tablet ("Wacom Intuos 2", format A3, 420 × 297 mm, frequency of 50 Hertz, accuracy 0.41 mm), allowing recording of all relevant information relative to the spatial parameters of written production.

#### *Stimuli and procedure*

In each task (copy, writing to dictation, and written naming), the numbers from 1 to 9 were presented in two sequences, random and ordered. In the random sequence, the numbers from 1 to 9 were presented in casual order. In the ordered sequence, the written or spoken word "count" instructed the subject to write down the counting sequence from 1 to 9 at a given rate determined by an alert sound. In both sequences, subjects had to write down the target stimulus as soon as the alert sound (lasting 1,000 ms) was presented.

In the random sequence of the copy task, Arabic digits were presented against a white background, in black Triplex Sans Light font 3 cm wide and 5 cm high (visual angle: 3.8° × 6.3°). Stimulus presentation was terminated by the experimenter who pressed a key on the keyboard as soon as the participant stopped writing. In the ordered sequence, the word “count” was presented for 3,000 ms, followed by nine sounds in sequence, one every 3,000 ms.

In the writing to dictation task, verbal numerals and the word “count” were recorded with a female voice and normalised to the same tonality with the software Audacity (a free software, Audacity Developer Team, 2007). Stimulus duration was 1,000 ms, and the inter-stimulus interval was controlled as for the copy task.

In the written naming task, arrays of black dots (diameter: 0.5 cm, visual angle: 0.6°) varying in numerosity from one to nine were visually presented. In each trial, the dots were randomly positioned within an imaginary central square (5 × 5 cm, visual angle 6.3° × 6.3°) resulting in different configurations. The ordered sequence was presented as in the copy task. Note that although production of the ordered sequences is identical across the tasks, we do not exclude differences in processing induced by the different contexts.

For each task, every digit was presented 5 times for each sequence type, for a total of 90 experimental trials. Each task was preceded by three practice sequences, two of which were ordered. Practice trials were repeated if subjects appeared uncertain about the procedure and discarded from all subsequent analyses. Subjects, who hold the pen with their dominant hand over the entire task, did not receive any visual feedback of their own graphic marks. Instructions required participants to move their hand to the starting position (centrally positioned on the inferior border of the tablet) after each trial. No other constraints were given in the instructions.

In order to familiarise participants to the script and to the apparatus, the first task for all the subjects was the copy task. The order of presentation of writing to dictation and written naming was counterbalanced across participants.

## Data analysis

Four subjects’ data were excluded from the analysis of the copy task because of a very high proportion of inaccurate recording (missing trials over 50%). For all remaining subjects, in all tasks, errors and ambiguous symbols were identified and not further analysed (42, 0.97%—in the copy task; 36, 0.83%—in the writing to dictation task; and 23, 0.53%—in the written naming task).

For all accepted trials, the smallest inscribing rectangle containing each digit written by each subject in each trial was computed. The horizontal coordinate of the rectangle barycentre (*X* centre), that is its distance from the left border of the drawing area ($X = 0$) expressed in mm, was the dependent variable (see Fig. 1). The mean value of the *X* centre for each digit was submitted to two repeated-measures analyses of variance. The first one explored the copy task with two within-subject factors: number size (with pairs of numbers 1–2, 3–4, 6–7, 8–9 merged together) and sequence (random, ordered).

In the second ANOVA, the performance in the two experimental tasks was analysed with task (writing to dictation, written naming), number size (1–2, 3–4, 6–7, 8–9), and sequence (random, ordered) as within-subject factors.

Whenever necessary, the Huynh–Feldt correction for repeated-measures analysis (Huynh and Feldt 1970; Huynh and Feldt 1976) was used to correct for violations of the sphericity assumption. The epsilon (ε) used to reduce the degrees of freedom, the original degrees of freedom, and the corrected *P*-values are reported.

Finally, the influence of numerical information on writing performance was further investigated by means of a regression analysis for repeated-measures data (Lorch and Myers 1990). Regression equations ($x = B \times NS + A$) were calculated using numerical magnitude (NS) as the predictor variable for each subject, for each task, and for

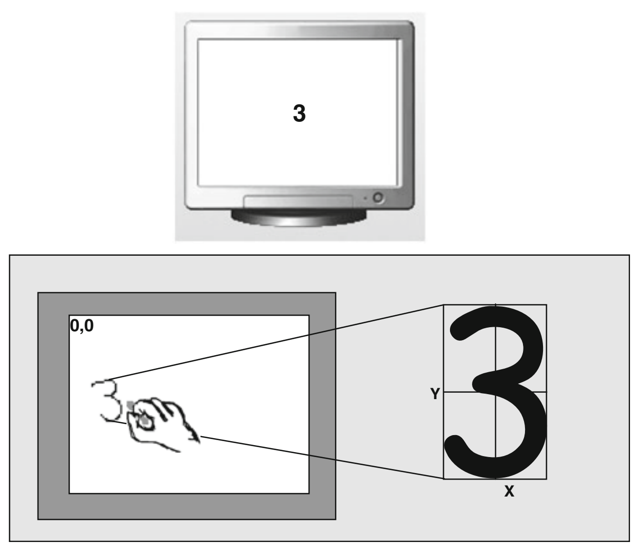


**Fig. 1** Dependent variable (*X* centre): the *X* and *Y* coordinates determining the centre of the *rectangle* including the reproduced digit. The *horizontal* coordinate of *X* centre is the distance from the *left border* of the drawing area (*X* coordinate of value 0) and the *rectangle’s* centre. The value in pixels was converted to mm (1 pixel = 0.41 mm)

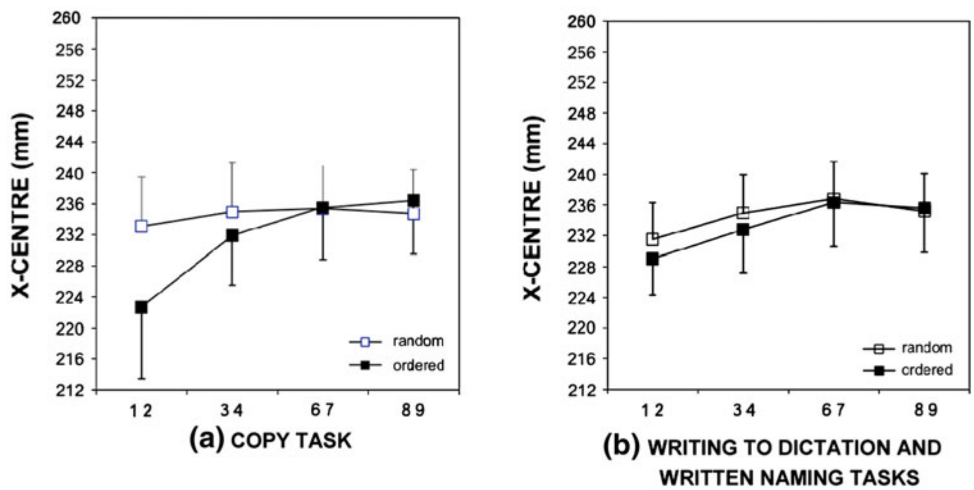


**Fig. 2** Experiment 1 (*writing of numbers*). Subjects' average *X* centre and ±SE bars of written production as a function of number size (1–2, 3–4, 6–7, 8–9) and sequence (random, ordered) in **a** copy task and **b** in writing to dictation and written naming tasks

each type of sequence. The slope coefficients (B) obtained from the regression were then contrasted to zero with a *t*-test analysis (see Lorch and Myers 1990; Fias et al. 1996).

Results

In the copy task ANOVA, the main effect of number size was marginally significant ($F[3,33] = 3.22$, $\varepsilon = .72$, $P = .054$), although planned comparisons[2] did not reveal significant differences between consecutive sizes (all $P > .1$; see Fig. 2a). The effect of sequence was also marginally significant ($F[1,11] = 3.74$, $P = .08$), while the interaction number size X sequence was not significant ($F[3,33] = 2.53$, $\varepsilon = .43$, $P > .1$).

In the other two experimental tasks, the effects of task and sequence were not significant ($F[1,15] = 2.06$, $P > .2$; $F[1,15] = 1.54$, $P > .2$). The main effect of number size was significant ($F[3,45] = 9.45$, $\varepsilon = .66$, $P < .001$; see Fig. 2b). Planned comparisons revealed the following: 1–2 vs. 3–4, $P < .05$, 3–4 vs. 6–7, $P < .01$, 6–7 vs. 8–9, n.s. Only the number size X sequence interaction was marginally significant ($F[3,45] = 2.43$, $P = .08$; all other interactions $P > .2$). Two separate ANOVAs for the two sequences replicated the number size effect: both in random ($F[3,45] = 5.33$, $P < .01$) and in ordered sequences ($F[3,45] = 10.47$, $\varepsilon = .58$, $P < .001$].

In relation to the regression analyses, in the copy task, the regression line is described by the following equations:

ordered sequence: $X_c = 1.83\ \mathrm{NS} + 309.7$;
random sequence: $X_c = 0.36\ \mathrm{NS} + 233.31$,

where $X_c$ is the *X* centre and NS is the number size.

The *t*-test on the slope coefficient was marginally significant in the ordered sequence only ($t(11) = 2.12$, $SD = 4.16$, $P = .06$, random sequence: $t(11) = 0.90$, $SD = 1.57$, $P = .39$), reflecting the contribution of number magnitude to the observed variable (with a positive slope observed in 11 participants).

In the writing to dictation task, the regression analysis revealed the following equations:

ordered sequence: $X_c = 0.81\ \mathrm{NS} + 227.56$;
random sequence: $X_c = 0.81\ \mathrm{NS} + 229.78$.

The contribution of number magnitude resulted significant in both sequences: in random, $t(15) = 2.14$, $SD = 2.10$, $P < .05$ (with a positive slope observed in 14 participants), and in ordered, $t(15) = 4.14$, $SD = 1.09$, $P < .001$ (with a positive slope observed in 15 participants).

This holds true also for the written naming task, where the regression line is described by the following equations:

ordered sequence: $X_c = 1.11\ \mathrm{NS} + 230.36$;
random sequence: $X_c = 0.28\ \mathrm{NS} + 234.67$.

The *t*-test on the slope coefficients was significant in both random $t(15) = 2.54$, $SD = .61$, $P < .05$ (with a positive slope observed in 11 participants) and ordered sequences $t(15) = 2.87$, $SD = 2.15$, $P < .01$ (with a positive slope observed in 14 participants).

## Discussion

Three main points may be drawn from the results of Experiment 1. First, overall written performance was characterised by a spatial dislocation of digits along the horizontal axis as a function of their magnitude: small digits were produced more to the left relative to larger ones. Second, the spatial dislocation was present in both ordered and random sequences; however, it was different across the tasks. In written naming and writing to dictation, the magnitude effect emerged in all sequences, while in the copy task, the spatial

[2] The Bonferroni correction was applied to all planned comparisons.

dislocation was marginal and limited to ordered sequences. In particular, the left to right spatial dislocation of number handwriting as a function of the digit magnitude is consistent with their spatial mapping on a mental number line, as if the activation of this representation had an effect on the arm movements responsible for the action endpoint, i.e., the specific location in the horizontal plane where handwriting takes place. Moreover, as reflected in the regression analyses, the relative position of the different digits was dislocated along the left to right horizontal direction (within a rather central area of the tablet) so that smaller numbers were written to the left of the larger ones. Critically, when writing was more than a simple copy, this occurred even when numbers had to be written in a random sequence, with no explicit reference to their intrinsic order.

These results are in line with the hypothesis that number processing interacts with action planning and/or execution. However, whether this effect is generated by the ordinal or the cardinal value of the numbers remains to be established. Indeed, non-numerical ordered sequences (e.g., letters, months, and days of the weeks) have been shown to produce magnitude-related effects such as the SNARC and the distance effects (Gevers et al. 2003; Gevers et al. 2004), with the first elements in the sequence behaving like small numbers and the last ones behaving like large numbers. To investigate whether the spatial dislocation in written performance was simply induced by access to order information, Experiment 2 seeks to replicate the findings from Experiment 1 using the letters of the alphabet as stimuli.

## Experiment 2. Writing of letters

Experiment 2 was similar to Experiment 1, except for the stimuli, which were the first nine letters of the Italian alphabet. Copy and writing to dictation were identical to Experiment 1. In addition, we presented participants with a task that required transcoding of letters so that the allograph to be produced must be internally activated. If the spatial dislocation in written performance derives from the activation of a quantity-related spatial continuum, the effects should not extend to non-numerical sequences, such as alphabetical characters. On the other hand, if the activation of ordinal information is responsible for the observed dislocation, the effects should emerge in the written performance of any ordered sequence.

### Materials and methods

#### *Subjects*

Sixteen right-handed undergraduate students (13 women and 3 men) from the University of Milano-Bicocca participated in this study; none of them participated in Experiment 1. The mean age was 25 (range 20–44). All participants had normal or corrected to normal vision and were naive about the hypotheses of the experiment.

#### *Stimuli and procedure*

The first nine letters of the Italian alphabet were employed for the three tasks: (i) copy from a model, (ii) writing to dictation, and (iii) transcoding from lower-case to upper-case letter. All tasks required written production of upper-case letters. The written stimuli were presented centrally against a white background, in black and bold Arial font of 60-point size. In the copy task, stimuli occupied a 2 × 2 cm (2.5° × 2.5° of visual angle) non-visible frame, while in the transcoding task, stimuli occupied a 1.3 × 2 cm non-visible frame (1.7° × 2.5° visual angle). The auditory stimuli were the names of the first nine letters of the alphabet and the word “go” acted as starting signal for ordered sequences. All were registered with a female voice equated for tonality by software Audacity. Each stimulus lasted 1,000 ms.

Experimental procedure, presentation time, and order of the tasks were identical to Experiment 1.

### Data analysis

Inspection of errors and inaccurate recordings led to the exclusion of 72 trials (1.7%) from all further analyses.

The smallest inscribing rectangle for each letter written by each subject in each trial was calculated. The horizontal coordinate of the barycentre (*X* centre), which is the distance from the left border of the drawing area, was used as the dependent variable (see Fig. 1). The mean value of the X centre for each letter was submitted to two repeated-measures analyses of variance. The first one explored the effects of position and sequence in the copy task with two within-subjects factors: letter position (with pairs of letters A–B, C–D, F–G, H–I merged together) and sequence (random, ordered). A second ANOVA was carried out for the two experimental tasks, with task (writing to dictation, transcoding), letter position (A–B, C–D, F–G, H–I), and sequence (random, ordered) as within-subjects factors.

Finally, as in Experiment 1, the influence of letter position on writing performance was further investigated by means of a regression analysis for repeated-measures data (Lorch and Myers 1990).

### Results

In the copy task (see Fig. 3a), a marginally significant effect of letter position was found ($F[3,45] = 3.7$, $\varepsilon = .45$, $P = .06$). Planned comparison revealed the following: A–B vs. C–D, $P < .05$, C–D vs. F–G, n.s., F–G vs. H–I,

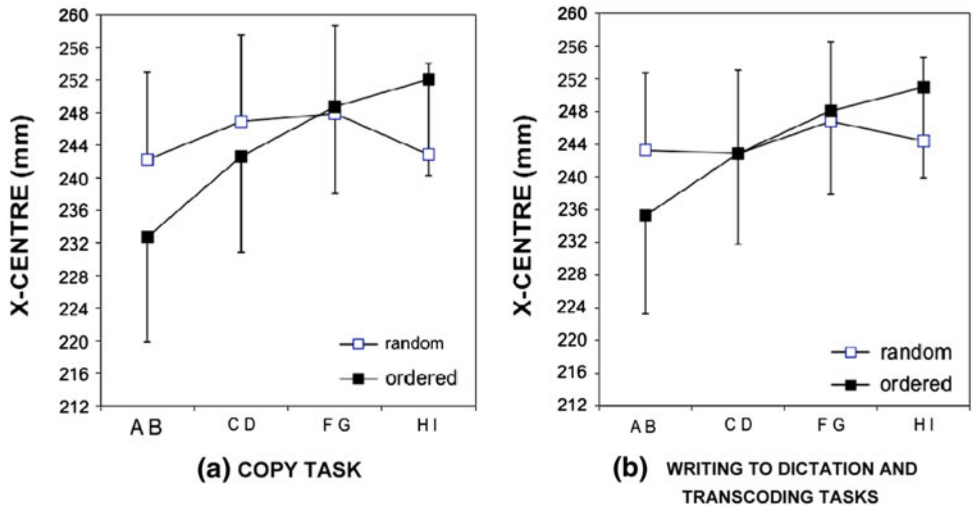


**Fig. 3** Experiment 2 (*writing of letters*). Subjects' average *X* centre and ±SE bars of written production as a function of *letters* alphabetical position (AB, CD, FG, HI) and sequence (random, ordered) in **a** copy tasks and **b** writing to dictation and transcoding from *lower-case* to *upper-case* tasks

n.s. The sequence effect was not significant ($F[1,15] < 1$, n.s.), nor the interaction letter position *X* sequence ($F[3,45] = 2.03$, $\varepsilon = .39$, $P > .2$).

In the analysis of variance for the two other experimental tasks, none of the main effects were significant (all, $P > .2$). Task *X* letter position was the only interaction marginally significant ($F[3,45] = 2.77$, $\varepsilon = .77$, $P = .07$). Two separated one-way ANOVAs for the two tasks showed a null effect of letter position (writing to dictation task: $F[3,45] = 2.55$, $\varepsilon = .46$, $P > .1$; transcoding task: $F[3,45] = 1.68$, $\varepsilon = .48$, $P > .2$). None of the other interactions reached significance (task *X* sequence, $F[1,15] < 1$, n.s.; letter position *X* sequence, $F[3,45] = 1.36$, $\varepsilon = .41$, $P > .3$; task *X* letter position *X* sequence $F[3,45] < 1$, n.s.).

The *t*-tests on the slope coefficients for each subject, task, and sequence did not reveal any effect of letter position on performance (all $P > .1$).[3]

## Discussion

Results of Experiment 2 are rather clear. When the writing output consists of letters, their relative position in the alphabet had a null or marginal effect on the movement endpoint. In fact, spatial dislocation of writing as a function of letter position in the alphabet was minimal and limited to the copy task. Although spatial coding seems to occur in the representation of any ordered information (Gevers et al. 2003, 2004), it seems reasonable to suggest that order is intrinsically relevant only for numbers. Accordingly, in writing performance, where no explicit lateralised movements or strict spatial constraints are imposed (cf. Fischer et al. 2003), the obligatory activation of a spatially oriented representation takes place and interacts with action planning only when numbers are involved.

## General discussion

The aim of the present study was to explore whether the automatic mapping of numbers in the representational space exerts an influence on the motor planning involved in number handwriting. In particular, we show that the automatic association between numbers and their relative position along an oriented spatial continuum induces spatial dislocations of the writing movement endpoints as a function of their magnitude. In particular, we measured the relative position on the horizontal axis of each single digit handwritten on a digitising tablet, under different task conditions. The results show that, across different tasks, number writing is characterised by a spatial dislocation of the digits as a function of their magnitude: small digits are produced leftwards relative to larger ones. Critically, this holds true not only for the ordered sequences but also for the random ones, where the overlearned left-to-right sensory–motor association evoked by a counting sequence is minimised. However, the regression analyses indicated that this applies only when writing is more than a simple copy, since in the copy task, the spatial dislocation of written

[3] In the copy task, the regression line is described by the following equations (in brackets *T* values against 0 and number of participants with a positive slope [*N*]): ordered sequence: $X_c = 2.53$ LP + 231.48 where $X_c$ is the *X* centre and LP is the letter position (*t*-test(15) = 1.57, SD = 14.31, $P = .14$ [$N = 12$]); random sequence: $X_c = 0.15$ LP + 243.77 (*t*-test(15) = 0.69, SD = 1.99, $P = .50$ [$N = 10$]). In the writing to dictation, the regression line is described by the following equations: ordered sequence: $X_c = 2.38$ LP + 232.26 (*t*-test(15) = 1.42, SD = 14.9, $P = .18$ [$N = 12$]); random sequence: $X_c = 0.49$ LP + 242.61 (*t*-test(15) = 1.73, SD = 2.53, $P = .1$ [$N = 9$]). In the transcoding task, the regression line is described by the following equations: ordered sequence: $X_c = 2.05$ LP + 235.65 (*t*-test (15) = 1.29, SD = 14.14, $P = .22$ [$N = 11$]); random sequence: $X_c = 0.05$ LP + 244.38 (*t*-test(15) = 0.48, SD = 0.98, $P = .64$ [$N = 8$]).

production emerged only for the ordered sequences. This result is in line with our prediction according to which the influence of a representational spatial mapping is maximised in tasks that require a deeper, although not necessarily semantic, processing of numbers. Indeed, in both writing to dictation and written naming, the target digit must be retrieved from memory and its graphemic representation must be activated, while copying may be easily accomplished by merely reproducing a visual model (Margolin 1984). Moreover, in the copy task, the written stimulus was available and centrally displayed and we may not exclude that it served as a visual cue for guiding the arm movement endpoints. This partially applies also to written naming although, in this case, the stimulus was visually more complex (patterns of dots vs. digits), and visually different from what was required to be produced. In the writing to dictation task, no visual cues were provided, and thus writing performance was free from visuo-spatial constraints.

Finally, we intended to verify whether the magnitude/motor interaction responsible for the spatial dislocation in number writing extends to non-numerical ordered sequences. Order has been shown to produce several magnitude-related effects, such as the SNARC and the distance effects (Gevers et al. 2003, 2004), and on these grounds, it has been suggested that any ordered sequences may be preferentially mapped onto a spatial mental representation (e.g., Van Opstal et al. 2009; Previtali et al. 2010). In the present study, number and letter writing are differently modulated by the implicit and irrelevant mapping of the ordinal trials in the representational space. In particular, the impact of a spatial mental representation on the motor planning associated with handwriting is limited to numerical sequences. Indeed, a dislocation in writing letters occurs marginally only in the copy task and only when trials are produced in ordered sequences. These results add to existing evidence pointing to behavioural (Turconi et al. 2006; Zorzi et al. 2006) and processing differences (Turconi et al. 2004; Badets et al. 2007) of ordinal and magnitude information. However, our results do not reveal whether the absence of the position effect in letter writing derived from a null or a weak mapping of letters on the representation space. In fact, spatial mapping may occur for different ordered sequences (not only numbers) although the intrinsic relevance and, consequently, the access to it are likely to differ for numerical, alphabetical, and other ordered sequences.

Overall, these findings extend previous evidence of an influence of numerical magnitude on motor outcomes, as shown by magnitude-space congruency effects in various tasks (Fischer 2003; Andres et al. 2004; Fischer et al. 2004; Ishihara et al. 2006; Badets et al. 2007). However, the novelty of the present study consists in showing that numerical information may impact on an overlearned complex motor plan, such as spontaneous handwriting. Yet, at present, we can only speculate if the processing of magnitude information exerts its influence on handwriting movement endpoints at the level of action planning or of motor execution (Andres et al. 2008; Fischer and Miller 2008). In fact, spontaneous handwriting does not allow us to disentangle between planning and execution of the arm movements implied in written production. Moreover, in contrast with paradigms adopting forced lateralised motor responses (Fischer 2003; Fischer et al. 2004; Ishihara et al. 2006), the spatial compatibility between magnitude and motor action is not dichotomical (left/right) but continuous along the horizontal axis. This implies that the location of handwriting is not wrong *per se* but slightly modulated by the relative position of the number along a representational continuum. On this ground, we did not expect subjects to self-correct or adjust their motor plans during execution (cf. Andres et al. 2008).

Finally, our results fit with the ATOM theory according to which the impact of magnitude information on motor action arises within the parietal cortex (Walsh 2003). The reported compatibility effect between spatial mapping of numbers in the representational space and their spatial dislocation in the horizontal plane reflects the interaction between number representation and writing movements. The involvement of the intra-parietal sulcus in supporting the visuo-spatial representation of numbers is well documented and universally accepted (Dehaene et al. 2003; Hubbard et al. 2005). Moreover, both neuropsychological and neuroimaging data point to the extensive involvement of the left inferior parietal lobe in subserving writing performance (Delazer et al. 2002; Harrington et al. 2007). Thus, the present study adds to the large body of evidence pointing to the parietal cortex as the crucial brain district where multi-dimensional magnitude information is integrated to subserve action (for a review, Bueti and Walsh 2009).

**Acknowledgments** We thank Alberto Riboldazzi for his help in collecting data for Experiment 1. This study was partially supported by a grant from University of Milano-Bicocca (FAR 2007) and a MIUR grant to LG.

## References

Andres M, Davare M, Pesenti M, Olivier E, Seron X (2004) Number magnitude and grip aperture interaction. Neuroreport 15:2773–2777

Andres M, Ostry DJ, Nicol F, Paus T (2008) Time course of number magnitude interference during grasping. Cortex 44:414–419

Badets A, Andres M, Di Luca S, Pesenti M (2007) Number magnitude potentiates action judgements. Exp Brain Res 180:525–534

Bueti D, Walsh V (2009) The parietal cortex and the representation of time, space, number and other magnitudes. Philos Trans R Soc B: Biol Sci 364:1831–1840

Casarotti M, Michielin M, Zorzi M, Umiltà C (2007) Temporal order judgment reveals how number magnitude affects visuospatial attention. Cognition 102:101–117

Chiou RYC, Chang EC, Tzeng OJL, Wu DH (2009) The common magnitude code underlying numerical and size processing for action but not for perception. Exp Brain Res 194:553–562

Cipolotti L, Butterworth B (1995) Toward a multiroute model of number processing: impaired number transcoding with preserved calculation skills. J Exp Psychol Gen 124:375–390

Dehaene S (1992) Varieties of numerical abilities. Cognition 44:1–42

Dehaene S, Akhavein R (1995) Attention, automaticity, and levels of representation in number processing. J Exp Psychol Learn Mem Cogn 21:314–326

Dehaene S, Cohen L (1995) Towards an anatomical and functional model of number processing. Math Cogn 1:83–120

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

Dehaene S, Piazza M, Pinel P, Cohen L (2003) Three parietal circuits for number processing. Cogn Neuropsychol 20:487–506

Delazer M, Lochy A, Jenner C, Domahs F, Benke T (2002) When writing 0 (zero) is easier than writing O (o): a neuropsychological case study of agraphia. Neuropsychologia 40:2167–2177

Deloche G, Seron X (1987) Numerical transcoding: a general production model. Hillsdale, New Jersey

Dodd MD, Stigchel SVd, Adil Leghari M, Fung G, Kingstone A (2008) Attentional SNARC: there's something special about numbers (let us count the ways). Cognition 108:810–818

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 2:95–110

Fischer MH (2003) Spatial representations in number processing: evidence from a pointing task. Vis Cogn 10:493–508

Fischer R, Miller J (2008) Does the semantic activation of quantity representations influence motor parameters? Exp Brain Res 189:379–391

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

Fischer MH, Warlop N, Hill RL, Fias W (2004) Oculomotor bias induced by number perception. Exp Psychol 51:91–97

Galfano G, Rusconi E, Umiltà C (2006) Number magnitude orients attention, but not against one's will. Psychon Bull Rev 13: 869–874

Galton F (1880) Visualised numerals. Nature 21:252–256

Gevers W, Reynvoet B, Fias W (2003) The mental representation of ordinal sequences is spatially organized. Cognition 87:B87–B95

Gevers W, Reynvoet B, Fias W (2004) The mental representation of ordinal sequences is spatially organised: evidence from days of the week. Cortex 40:171–172

Harrington GS, Farias D, Davis CH, Buonocore MH (2007) Comparison of the neural basis for imagined writing and drawing. Hum Brain Mapp 28:450–459

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

Huynh H, Feldt LS (1970) Conditions under which mean square ratios in repeated measurements designs have exact F-distributions. J Am Stat Assoc 65:1582–1589

Huynh H, Feldt LS (1976) Estimation of the box correction for degrees of freedom from sample data in randomized block and split-plot designs. J Educat Stat 1:69–82

Ishihara M, Jacquin-Courtois S, Flory V, Salemme R, Imanaka K, Rossetti Y (2006) Interaction between space and number representations during motor preparation in manual aiming. Neuropsychologia 44:1009–1016

Lindemann O, Abolafia JM, Girardi G, Bekkering H (2007) Getting a grip on numbers: numerical magnitude priming in object grasping. J Exp Psychol Hum Percept Perform 33:1400–1409

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

Margolin DI (1984) The neuropsychology of writing and spelling: semantic, phonological, motor and perceptual processes. Q J Exp Psychol 34:459–489

Moretto G, di Pellegrino G (2008) Grasping numbers. Exp Brain Res 188:505–515

Moyer RS, Landauer TK (1967) Time required for judgements of numerical inequality. Nature 215:1519–1520

Nicholls MER, Loftus AM, Gevers WIM (2008) Look, no hands: a perceptual task shows that number magnitude induces shifts of attention. Psychon Bull Rev 15:413–418

Previtali P, de Hevia MD, Girelli L (2010) Placing order in space: the SNARC effect in serial learning. Exp Brain Res 201:599–605

Priftis K, Zorzi M, Meneghello F, Marenzi R, Umiltà C (2006) Explicit versus implicit processing of representational space in neglect: dissociations in accessing the mental number line. J Cogn Neurosci 18:680–688

Restle F (1970) Speed of adding and comparing numbers. J Exp Psychol 83:274–278

Schwarz W, Müller D (2006) Spatial associations in number-related tasks: a comparison of manual and pedal responses. Exp Psychol 53:4–15

Seron X, Noël MP (1995) Transcoding numbers from the Arabic code to the verbal one or vice versa: how many routes? Math Cogn 1:215–243

Shaki S, Fischer MH, Petrusic WM (2009) Reading habits for both words and numbers contribute to the SNARC effect. Psychon Bull Rev 16:328–331

Song J-H, Nakayama K (2008) Numeric comparison in a visually-guided manual reaching task. Cognition 106:994–1003

Turconi E, Jemel B, Rossion B, Seron X (2004) Electrophysiological evidence for differential processing of numerical quantity and order in humans. Cogn Brain Res 21:22–38

Turconi E, Campbell JID, Seron X (2006) Numerical order and quantity processing in number comparison. Cognition 98:273–285

Van Opstal F, Fias W, Peigneux P, Verguts T (2009) The neural representation of extensively trained ordered sequences. NeuroImage 47:367–375

Walsh V (2003) A theory of magnitude: common cortical metrics of time, space and quantity. Trends Cogn Sci 7:483–488

Wood G, Nuerk HC, Willmes K (2006) Crossed hands and the SNARC effect: a failure to replicate Dehaene, Bossini and Giraux (1993). Cortex 42:1069–1079

Zbrodoff NJ, Logan GD (1986) On the autonomy of mental processes: a case study of arithmetic. J Exp Psychol Gen 115:118–130

Zorzi M, Priftis K, Meneghello F, Marenzi R, Umiltà C (2006) The spatial representation of numerical and non-numerical sequences: Evidence from neglect. Neuropsychologia 44: 1061–1067