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BEYOND NUMBERS: THE ORIGIN OF SPATIAL ASSOCIATIONS OF ORDINAL INFORMATION

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General introduction

The spatial organization of mental representations is neither a new nor an unexplored concept (Kosslyn et al., 1989), although this issue has recently received renewed consideration mostly due to the influence of the spatially oriented numerical representation (Dehaene et al., 1993; for a review see Hubbard et al., 2005), according to which increasing magnitudes are spatially ordered from left to right. The strongest support for this hypothesis comes from the SNARC effect (Spatial Numerical Association of Response Codes [Dehaene et al., 1993]), according to which small numbers elicit faster left-sided responses while large numbers evoke faster right-sided responses (Dehaene et al., 1993).

This association between numbers and space is not so stable as it would be expected, but it depends on contextual aspects. Indeed there is evidence suggesting that numbers are not intrinsically related to space, but that this association appears to be flexible. First of all, the association between left or right hand and small or large numbers depends on the range in which numbers occur, for example, numbers 4 and 5 elicit faster left than right responses when the numbers ranged from 4 to 9, but elicit faster right than left responses when the numbers ranged from 1 to 5 (Dehaene et al., 1993; Fias et al., 1996). Moreover, the spatial association depends also on the mental imagery, that is, when participants were asked to imagine numbers displayed on a clock face the SNARC effect reversed (Bachtold et al., 1998). Another example of flexibility in number-space associations comes from cultural studies that show how the SNARC effect can be influenced by the direction of the text read before the numerical task (Shaki & Fischer, 2008). Finally, it has been showed that the creation of new short-term memory associations between numbers and response side modulates the SNARC effect (Notebaert et al., 2006). All these results seem to suggest that the interaction between numbers and space is constructed during task execution, so it might be temporary and with no implication of long-term memory associations, which could suggest a crucial role of working memory. This hypothesis has been tested by evaluating the effect of working memory load on the SNARC effect and results confirmed the critical role of working memory resources in determining the SNARC effect (Herrera et al., 2008; Van Dijck et al., 2009).

Importantly, spatial compatibility effects have been observed not only with other quantitative dimensions (Ishihara et al., 2008; Rusconi et al., 2006), but critically with non-quantitative ordinal sequences, such as letters, days and months (Gevers et al., 2003; 2004). This suggests that also the mental representation of a non-numerical ordinal sequence is spatially coded and this spatial component is automatically activated. So far, further investigations on the role of ordinal information rather than the magnitude information in determining the spatial association between (numerical and non-numerical) sequences and response side are still missing.

This contribution aimed to explore the origin of spatial associations of numerical and ordinal information, examining potential mechanisms that could determine the spatial coding, providing three studies that will further investigate different aspects recently reported in the literature.

1. Contribution of the thesis

The first study (Chapter 2) takes in consideration finger counting strategies as determinants of the spatial organization of mental number representation. Indeed, it has been recently hypothesized that the first hand used to count with fingers could influence the SNARC effect (Fischer, 2008). Particularly, a large group of Scottish participants were asked to fill a written questionnaire in order to evaluate their number-to-finger assignments in counting with fingers. According to the preferential direction of finger counting (i.e., the order in which hands are used to count on fingers), two subgroups of left-hand (N = 53) and right-hand starters (N = 47) were asked to perform a parity judgment task and results showed different SNARC effects, with only the former group presenting with a significant canonical left-to-right numerical mapping. The aim of the study is first to test the extent to which handedness predicts finger counting direction in an Italian population and, more critically, to evaluate whether finger counting routines influence the spatial mapping of numbers as indexed by the SNARC effect. It is clear that there is an interaction between finger counting strategies and numerical judgments, but the aim of the study is to investigate how much the strength of the spatial numerical association varies as a function of finger counting direction. In order to assess the handedness, *Edinburgh Handedness Inventory* (Oldfield,

1971) has been completed (Experiment 1a) and regarding the finger counting strategy the direct observation (Experiment 1b) has been considered the ideal method for testing it (Sato & Lalain, 2008). Results will show the presence of a link between handedness and finger counting direction, at least in Italian population, that let to classify participants in left-starters (left-handed) and right-starters (right-handed). Particularly, these two groups performed a parity judgment task (Experiment 2) that showed a similar SNARC effect in left- and right-starters, suggesting that the embodied number-space association built up from finger counting routines does not critically shape the spatial mapping of numbers at the representational level.

In the second study (Chapter 3) the activation of the spatial component in mental representation of non-numerical ordinal sequences (Gevers et al., 2003; 2004) has been investigated to test the hypothesis according to which a spatial organization may constitute the privileged way of mentally organizing serial information. To this aim, the study in Chapter 3 investigates whether a spatial coding occurs for a newly learned ordered sequence of words. In particular, a list of nine words has been learned through both visual and auditory presentations during three different sessions and in the third session participants were asked to classify the memorized words/images. Three different classification tasks (Experiments 3, 4 and 5) and one detection task (Experiment 6) have been adopted and results confirmed that stimuli at the beginning of the list were responded to faster with the left than with the right hand, whereas words at the end of the list were responded to faster with the right than the left-hand, mimicking the standard SNARC effect, even when order information was irrelevant to the task. Thus, a visuo-spatial internal representation seems to reflect the spontaneous spatial mapping of ordered information, independently from its nature. In particular, a mental spatial coding takes place even for information that is newly acquired and that does not convey either magnitude or intrinsic ordinal meaning.

Finally, the third study (Chapter 4) further investigates the role of working memory in the spatial representation of order. In particular, the following questions will be addressed: if a spatial organization of newly acquired ordered information occurs (i.e., the study in Chapter 3, Previtali et al., 2010), which factors do determine the emerging spatial mapping? Yet, is order information processed by dedicated order-related mechanisms, i.e., scanning and long-term memory examination, equally involved in processing numbers and other ordered sequences (i.e., months) (Franklin et al., 2009)? Or alternatively, is the spatial coding not inherently associated to number or to other learned sequences and is it constructed during task execution (Van Dijck & Fias, 2011)? To distinguish between the role of working memory and of long-term memory associations as determinants of the SNARC effect, subjects were instructed to perform four classification tasks (Experiments 7, 8, 9 and 10) on digits memorised in random order in working memory. Results indicate that the spatial–numerical associations typically observed with numbers have their origin in the positional coding in working memory.

In conclusion, overall the data so far suggest that numerical magnitude is coded as a function of its serial position within a specific number range, and this hypothesis well explains the observed variability in number-space associations (Bachtold et al., 1998; Fischer et al., 2010; Notebaert et al., 2006). This working memory account (Van Dijck & Fias, 2011) explains also why non-numerical information with an intrinsic ordinal structure (Gevers et al., 2003; 2004) or over-learned new sequences (Previtali et al., 2010) evoke SNARC-related phenomena.

Future studies will further clarify the mechanisms involved in the spatial coding in working memory and the complex interaction between short- and long-term memory systems mediating processing of order information.

Chapter 1

The mental representation of ordered sequences

The ability of coding sequential order of events is one of the oldest critical investigated domains (Ebbinghaus, 1913; Young, 1968). Indeed, it is essential not only to keep trace of events, but to maintain the order in which actions and facts follow one another. Sometimes knowing “what” needs to be remembered is not enough, as some circumstances require to remember “when”, in which order, the information occurred (Marshuetz, 2005). One clear example is language acquisition and production where a stable temporary storage of ordered items (i.e., words) is crucial to any learning progress (Gathercole & Baddeley, 1990; Burgess & Hitch, 1999). It is worth noticing that order is critical also to most daily activities, such as, for example, in cooking that requires knowledge of the correct sequence of actions in order to obtain an acceptable result (Marshuetz & Smith, 2006).

Many studies have focused on how ordinal information is mentally represented, but originally the attention has been centered only on numbers and their representational effects (see below). Subsequently, the interest has been shifted even toward non numerical ordinal series that shared with numbers the characteristics of being sequentially ordered. The first part of this chapter will focus on the well-studied mental representation of numbers and the spatial compatibility effects it yields, the second part will discuss analogies and discrepancies with the other quantitative or just ordered sequences.

1. The mental representation of numbers

It is incontestable that the systematic use of numbers in daily life is essential for comparing sizes, counting elements, measuring distances, and even influencing the social life (Bynner & Parsons, 2006). Several models have been implemented for explaining numerical processes and mental number representation, taking into consideration how properties such as magnitude and parity are accessed (Campbell & Clark, 1988; McCloskey, 1992; Noël & Seron, 1992; Dehaene, 1992).

The large recent interest in the mental number representation comes from the metaphorical description of the *mental number line*, adopted to illustrate how numbers are mentally organized (for a review see Fias & Fischer, 2005; Hubbard et al., 2005; Wood et al., 2008). According to this hypothesis, the number representation is spatially oriented, with increasing magnitude mentally organized from left-to-right, at least in Western cultures (see below). The connection between numbers and space has been widely investigated, but the first illustration of this association corresponds to the *SNARC* (Spatial–Numerical Association of Response Codes) effect

(Dehaene et al., 1993). In the typical paradigm, during a parity judgment task (i.e., categorizing 1-to-9 numbers as odd or even pressing left or right buttons) Western participants responded to faster with the left than with the right hand when small numbers (e.g., 1 and 2) were classified, and on the contrary, they responded to faster with the right than with the left hand to large numbers (e.g., 8 and 9). Since the very first report, a considerable number of contributions specifically focused on the activation of the spatial representation as an automatic process. For example, the SNARC effect emerges also when numbers processing is not required for solving the task, as in physical matching (e.g., "2" and "two" are responded as "different", Dehaene & Akhavein, 1995), phoneme monitoring (i.e., judging whether a phoneme is included in numerical stimuli; Fias et al., 1996), and orientation judgment (i.e., determining the orientation of non-numerical stimuli superimposed on an irrelevant digit; Fias et al., 2001a). Interestingly, a completely spontaneous number-space association has been recently reported, showing that small numbers were randomly generated when participants faced leftward and, on the contrary, large numbers were generated when participants faced rightward (Loetscher et al., 2008). Moreover, not only numerical judgments and spatial attention are influenced by magnitude, but also goal-directed actions (i.e., classifying digits as odd or even by pointing with one hand to a left or right button; Fischer, 2003) and eye movements (i.e., an attentional shift to the left or right visual field was evoked by the presentation of irrelevant small or large numbers respectively; Fischer et al., 2004; Schwarz & Keus, 2004) can be modulated by numerical magnitude. In addition, even grip aperture while programming grasping movements appeared influenced by number magnitude, that is, when a numerically large digit was printed on the object to be grasp the aperture was larger than when the printed digit was numerically small (Andres et al., 2008).

A further extensively reported indication of the spatial feature of numerical representation is the *distance effect*, i.e., the ability to discriminate between two numbers improves as the numerical distance between them increases (Moyer & Landauer, 1967). Several models have explained this effect taking into account the overlapping representation of adjacent magnitudes along the *mental number line* (Dehaene & Changeux, 1993; Piazza et al., 2004), although recently a spatial component has not been considered essential for describing the representation of number magnitude (Verguts et al., 2005; Van Opstal et al., 2008). In fact, while previously the *mental number line* has been considered to be even homeomorphic to the representation of physical space (Stoianov et al., 2008), evidence in favor of dissociable mechanisms operating in number and space processing has been reported (Doricchi et al., 2005).

To sum up, there is agreement about the number-space interactions, mostly emerging as associations between small numbers and the left-side of space and large numbers and the right-side of space, but the origin of this spatial numerical association appears not completely understood. Among other interpretations, some evidence supports a crucial role of reading habits in shaping the spatial direction of numerical mapping (Dehaene et al., 1993; Shaki & Fischer, 2008), while other emphasizes the link between finger counting routine and spatial coding of numbers (see Fischer & Brugger, 2011). (These aspects will be further described below).

1.2 Cultural differences

The first original study describing the SNARC effect pointed to the direction of the reading-writing system as a critical factor shaping the left-to-right numerical mapping in Western countries, reporting asymmetries between French and Iranian populations (Dehaene et al., 1993). Confirming this hypothesis, Arabic (i.e., right-to-left readers) mono-literates showed a faster naming of the larger number between two when it was displayed on the left compared to the right side, a phenomenon that appears reduced in Arabic-English bi-literates (Zebian, 2005).

Further studies investigating bilingual populations showed an influence of the scanning habits direction on the spatial association of numbers, reporting a modulation of the SNARC effect in bilingual Russian–Hebrew. Specifically bilinguals showed a standard SNARC effect after reading Cyrillic script (i.e., left-to-right) that was significantly reduced after reading Hebrew script (i.e., right-to-left) (Shaki & Fischer, 2008). Recently, a reversed SNARC effect was documented with Palestinians (i.e., right-to-left readers) but not with Israeli participants who share the same scanning habits direction (Shaki et al., 2009), indicating that reading direction might be not the only determinant of the SNARC effect. In fact, Israeli population reads text right-to-left but Arabic numbers left-to-right, inducing probably an interaction between this two opposite spatial associations, i.e., from number processing and from reading. The hypothesis of multiple spatial associations has been recently evaluated by looking at the SNARC effect before and after reading a text with small or large numbers placed on the left or right side of text lines in English and Hebrew populations (Fischer et al., 2010). The results showed that the position of numbers within identical text changed the spatial associations of these numbers confirming how reading direction is not the only factor influencing the SNARC, probably determined by multiple spatial associations. In fact, authors suggest that the SNARC effect reflects recent individual experienced spatial–numerical mappings, as for example in the referred study, reading habits and physical position of numbers in the space (Fischer et al., 2010).

Furthermore, in a number words bisection task, French-speaking subjects' performance reflected a leftwards shift of the midpoint for small numbers in both canonical (i.e., ONEONE) and in mirror words (i.e., OWTOWT), regardless of the manipulated (i.e., canonical or mirror words) reading direction (Calabria & Rossetti, 2005).

Overall, these studies show that the extent to which reading direction shapes the spatial mapping of numbers is still controversial. In addition, very recently the hypothesis that the direction of the SNARC effect is not culturally-fixed has been proposed. For example, it has been reported that, in the Hebrew population, the SNARC effect varied as a function of the task instructions, i.e., when it was required to process the ordinal information a reversed right-to-left SNARC effect was observed, while, on the contrary, when magnitude information was emphasized a regular left-to-right SNARC effect emerged (Shaki & Gevers, 2011).

1.3 Different accounts for the SNARC effect

For long time, the *mental number line hypothesis* has been considered as the only possible explanation of the SNARC and the distance effects, originating from a direct mapping between the position of a number on an internal spatial representation and the corresponding response location in the external space.

Recently, the SNARC effect has received an alternative interpretation based on the *polarity correspondence principle*, according to which bipolar dimensions undergo a verbally mediated spatial coding. In particular, it is assumed that number magnitudes (small and large) and responses (left and right) are coded at an intermediate level on a bipolar dimension and corresponding polarities induce faster response selection (Proctor & Cho, 2006). Particularly, small numbers ([-] polarity) are responded to faster with the left hand ([-] polarity) and large numbers ([+] polarity) with the right hand ([+] polarity).

An alternative view on the SNARC effect is provided by a *multiple-layers computational model* integrating both mental number line and polarity correspondence positions (Gevers et al., 2006). Specifically, a spatial representation (bottom layer) interacts with an intermediate level of representation where numbers are automatically categorized either as small or large (or categorically coded according to the task demands, e.g., odd-even), and associated, at the top layer, with spatially defined responses. Extending this model, an abstract spatial code, i.e., categorization as ‘‘left” or ‘‘right”, has been successively introduced before activating the response (Notebaert et al., 2006).

These *categorical accounts* have been empirically confirmed using a magnitude comparison task, where, instead of left and right classifications, participants responded to a location (i.e., “close to” or “far from” the initial finger position) (Santens & Gevers, 2008). According to the *mental number line hypothesis*, being the fixed reference for magnitude comparison number 5, faster close than far responses for numbers 4 and 6 and faster far than close responses for numbers 1 and 9 were expected. On the contrary, an association between verbal concepts emerged, that is, small numbers (i.e., 1 and 4) were responded to faster with the “close” response and large numbers (i.e., 6 and 9) were preferentially associated to “far” responses, corroborating the *categorical account*.

More recently this evidence has been further supported, directly contrasting the visuo-spatial (i.e., the *mental number line*) and the verbal-spatial (i.e., *categorical accounts*) coding. In doing so, response buttons were labelled from trial to trial by describing words (i.e., “left” and “right”) and participants had to classify numbers, for example as odd or even, responding according to labels and not to the hands position (Gevers et al., 2010). Both visuo-spatial and verbal coding are sufficient to induce the SNARC effect separately, but when they were pitted against one another the verbal coding was observed, both in parity judgment and in number comparison tasks. This contribution does not exclude the existence of the visuo-spatial coding, but results suggest that the origin of the number-space interactions is not exclusively determined by a visuo-spatial representation as it was previously conceived by the *mental number line hypothesis*.

Very recently, considering that number-space associations are not steadily determined but flexible (Bachtold et al., 1998; Notebaert et al., 2006; Ben Nathan et al., 2009), and taking into account the working memory resources in yielding a SNARC effect (Herrera et al., 2008; Van Dijck et al., 2009), a new *working memory account* for spatial-numerical associations has been proposed (Van Dijck & Fias, 2011). According to this hypothesis, short-term numerical representations are created during task execution and the SNARC effect arises from the temporary spatial associations between stimuli and responses constructed for solving the task. (This account will be fully explained in the fourth chapter).

All these interpretations assume the associations between space and numerical magnitude as *disembodied*, as the SNARC effect persists for example when hands are crossed (Dehaene et al., 1993; but see also Wood et al., 2006), indicating that the spatial association between numbers and response side reflects the correspondence between small and large magnitude and left or right side of space respectively. In contrast, a recent hypothesis related to the *embodied* cognition approach suggested a crucial role of finger counting as determinant of spatial numerical associations ("*manumerical cognition*", Fischer, 2008).

2. Numbers within hands

The use of fingers and other body parts to count and express numerosities is a spontaneous and universal practice and it has been reported since the pre-historic age (Ifrah, 1981), although highly variable across cultures. For example, for some tribes people (i.e., New Guineans), counting practice includes the whole body surface, as they orderly name and touch parts of the body starting with the little finger of the right hand and ending with the left little finger, passing through the wrist, elbow, shoulder, eyes, nose, mouth and ears (Ifrah, 1985), providing a track of the counted elements. With regard to the hands, while some ancient cultures, such as the Romans, used the left hand alone to sign even large numerosities, e.g., 99, in others, such as the Greeks, the right-hand was used as a counting tool (Lindemann et al., 2011).

Importantly, finger counting routines play a supportive role across development, well reflected by their massive use in the acquisition of simple arithmetic. Although the use of fingers mainly characterises the initial stage of learning, this practice evolves with the increasing mastery of arithmetic knowledge (Jordan et al., 2008). Accordingly, indirect evidence for the role of fingers in supporting numerical development comes from studies reporting finger gnosis as a significant predictor of arithmetic performance in school-aged children (Fayol et al., 1998; Noël, 2005; Gracia-Bafalluy & Noël, 2008).

Recently, the long-lasting link between finger counting and number processing has received renewed attention within the *embodied cognition* *approach*, according to which cognitive processes are deeply shaped by the body's interaction with its environment (Wilson, 2002; Gibbs, 2006).

2.1 The link between finger counting and number processing

Several studies supported the hypothesis that number-to-finger associations influence number processing (Sato et al., 2007; Domahs et al., 2011; Fischer & Brugger, 2011) and modulate numerical mental representation (Di Luca et al., 2006; Domahs et al., 2010; Fischer, 2008). Specifically, there is evidence for an influence of finger counting direction on the direction of the mental numerical representation (Fischer, 2008) as well as for the specific structure of the finger counting system (e.g. the sub-base-five system) both on children's mental calculation (Domahs et al., 2008) and on adults' single-digit number comparison (Domahs et al., 2010). However, the functional relationship between fingers and number representation appears less obvious in specific sensory conditions. For example, it is worth noting that although blind children use their fingers in a less canonical way and less spontaneously than sighted children (Crollen et al., 2011), blind and sighted adults showed similar features in their mental representation of numbers (Castronovo & Seron, 2007; Sallilas et al., 2009). These results suggest that the contribution of finger counting to the mapping of numbers in the representational space may be less critical than considered in the "*manumerical cognition*" hypothesis.

However, both neuroanatomical and behavioral evidence suggested that finger counting habits may influence number processing over the life span. The neuro-functional link between fingers and numbers is not new to the neuropsychological literature in which the concomitant impairment of finger discrimination and calculation is essential to the classical Gerstmann syndrome (Gerstmann, 1940). Similarly, a transient impairment in finger schema representation and number processing has been induced by a virtual lesion (TMS) to the left angular gyrus in healthy subjects (Rusconi et al., 2005). Crucially, the systematic and long-lasting use of motor counting behavior during development has been considered a determining factor for the functional link between neural motor circuits and numerical processing. Accordingly, activation of the left precentral gyrus has been reported during simple calculation (Pesenti et al., 2000; Zago et al., 2001) and other number tasks (Pinel et al., 2001) suggesting a residual activation of cortical finger representation during symbolic number processing. Additional evidence comes from MEP studies, reporting an increase in hand muscle excitability while providing verbal responses to not only enumeration tasks (Andres et al., 2007) but also for number parity judgments (Sato et al., 2007).

Behavioral data added evidence to the role of finger counting in modulating the numerical mapping on the representational space. For example, it has been shown that during a task of identification of Arabic digits responding with all fingers according to different mappings, a preferential association of digits 1 to 5 with the right-hand fingers and digits 6 to 10 with the left-hand fingers emerged (Di Luca et al., 2006), reflecting a preference of the finger counting and not of the mental number line (i.e., association of the left hand to small numbers and of the right hand to large numbers) mapping. A further support to the embodied numerosities hypothesis has been provided by the reported modulation of finger counting direction on the mental number representation (Fischer, 2008). In this contribution it has been assumed that the first hand used to count with fingers influences the SNARC-effect, that is, participants who started to count on fingers with the left hand showed a canonical left-to-right mental representation of numbers, while subjects starting to count with the right hand showed a weaker or reversed SNARC effect.

Importantly, all the studies discussed so far intended to describe the spatial organization of mental numbers representation, focusing researches on the semantic magnitude information, being automatically activated in number processing. However, the information that numbers convey is not only related to magnitude, but it is intrinsically linked also to the position of numbers within the numerical sequence. For example, the number 2 could describe a specific quantity, e.g., *two* objects, as well as the order in a sequence, e.g., the *second* position. This ordinal information does not represent a prerogative feature of numbers, as it characterises any other ordered series (i.e., days, months and alphabet). Hence, the compatibility stimulus-response effect described for numbers (see above) may reflect an access to ordinal, and not specific numerical, information.

3. The mental representation of not-numerical ordered sequences

To test the potential spatial nature of any magnitude-related aspect, several behavioural effects observed in number processing have been investigated with non-numerical quantitative dimensions. For example, with different non-numerical magnitudes spatial stimulus-response compatibility effects (e.g., the SNARC effect) have been described. In fact, time (Ishihara et al., 2008) and pitch (Rusconi et al., 2006), which are intrinsically ordered, elicited faster left-side responses to early onset timing and low-frequency pitches and faster right-side responses to late onsets and high-frequency pitches, indicating a congruency effect comparable to the SNARC effect.

Importantly, the very first study using a letter classification task did not reveal a response-side in correspondence to the first or last alphabetic positions (Dehaene et al., 1993). However, a spatial coding of ordered non-numerical stimuli was more recently reported, describing a SNARC effect, i.e., an association between the left hand and stimuli at the beginning of sequences and between the right hand and stimuli at the end of sequences, and a distance effect with letters, months and days (Gevers et al., 2003; Gevers et al., 2004). Furthermore, as it was described for numbers, these spatial compatibility effects emerged when ordinal information was both relevant and irrelevant to the task, indicating an automatic activation of the spatially organized mental representation.

Yet, it remains to establish to what extent magnitude and ordinal information processing are mediated by the same or distinct cognitive mechanisms.

3.1 Evidence for a link between numbers and other ordinal sequences processing

Several studies have provide evidence favoring similar mechanisms involved in numerical and, more generally, ordinal information processing. A well-known phenomenon such as the distance effect (Moyer & Landauer, 1967) has been described for both numerical stimuli, even using different formats (Foltz et al., 1984), and non-numerical ordinal sequences, i.e., letters (Eger et al., 2003; Gevers et al., 2003; Hamilton & Sanford, 1978; Jou, 2003; Taylor et al., 1984) and months (Gevers et al., 2003). Furthermore, as illustrated above, the SNARC effect observed with letters, months (Gevers et al., 2003) and other quantitative dimensions (Rusconi et al., 2006; Ishihara et al., 2008), in addition to interactions among duration, order and spatial dimensions in time (Conson et al., 2008), suggest the possible existence of a shared spatially-coded system. This hypothesis of a generalized magnitude system for representing number and non-numerical quantities is not new. In fact, commonalities between time, space, number, size, speed and other magnitudes have been proposed in a *theory of magnitude* (ATOM; Walsh, 2003; Bueti & Walsh, 2009). According to Walsh's theory, magnitudes share common processing mechanisms and they are linked in order to guide action, for example for estimating quantitative dimensions such as length or distance.

Importantly, not only similar effects emerge with numbers and other ordered stimuli, but also a reverse distance effect and an absence of it were observed processing months of the year as well as numbers (Franklin et al., 2009). In fact, analogous order-related results were reported with both numbers and months as stimuli: a reverse distance effect emerged when comparing month crossing a year and comparing numbers crossing the decade and no effects appeared when months were in the same calendar year and numbers within the same decade.

Moreover, neuroimaging evidence corroborates this hypothesis, showing how number and ordinal information processing activate partially overlapping cerebral areas. Different parietal regions are involved in number processing (Dehaene et al., 1990; Chochon et al., 1999; Pesenti et al., 2000; Pinel et al., 2001; Eger et al., 2003; Fias et al., 2003;), but it is the anterior part of the horizontal segment of the intraparietal sulcus (hIPS) that was indicated as the contributing area for numerical quantity coding (Dehaene et al., 2003). Similarly, it has been shown that hIPS was also involved in non-numerical ordinal sequences processing, i.e., letters (Fias et al., 2007) and months (Ischebeck et al., 2008).

Finally, neuropsychological studies provide further evidence that different ordered quantities share cognitive representations. Indeed, a patient with a deficit in processing numbers and non-numerical sequences (i.e., letters, days and months) has been described (Cipolotti et al., 1991).

Furthermore, a semantic dementia patient with a severe deficit across several semantic categories was described to be selectively preserved in processing both numerical and non-numerical sequences (Thioux et al., 1998). Another indication comes from left neglect patients, reporting a similar shift (i.e., rightward) indicating the numerical (Zorzi et al., 2002) or timing (Basso et al., 1996) mid-point of two anchor values, even if contrasting results were found (see below).

Despite converging evidence in support of similar mechanisms mediating any ordinal information, whether numerical or not, some studies reported contrasting results, keeping the debate still open.

3.2 Evidence for distinct numbers and other ordinal sequences processing

Although there is much evidence for a shared quantitative representation (see above), double dissociations between numerical elaboration and serial information processing were firstly reported in the neuropsychological literature. A striking single-case study showed that impaired processing of number quantitative information may dissociate from intact processing of numerical ordinal information (Delazer & Butterworth, 1997; Dehaene & Cohen, 1997). Moreover, the opposite dissociation was also reported, represented by patients with preserved numerical skills despite a deficit in tasks requiring processing of ordered series (Dehaene & Cohen, 1997). These case studies clearly suggest that quantity and sequence order processing are mediate by distinct brain structures (Turconi & Seron, 2002).

The hypothesis of spatial representation as a specific property of numbers is further supported by studies reporting of neglect patients' performance in the mental bisection of numbers, letters and months (Zorzi et al., 2006). Indeed, results showed a rightward bias, modulated by interval length, and a cross-over effect in bisecting number intervals and, in contrast, different patterns in bisecting letter intervals (i.e., a rightward bias not modulated by length and absence of cross-over effect) and month intervals (i.e., a leftward bias).

In agreement with these results, an electrophysiological study showed similar behavioral effects (i.e., the distance effect) for both quantity and order although these resulted associated to different spatio-temporal courses in parietal and prefrontal cortices, e.g., the distance effect appeared earlier and was larger on the left hemisphere for quantity processing, while it was delayed and bilateral for order processing (Turconi et al., 2004). More recently, processing of numerical order information, adopting an *order judgment* task (e.g., "ascending or descending order of two presented numbers"), and processing of numerical quantity, using a *quantity comparison* task (e.g., "which is the larger between two presented numbers") have been directly compared. Results showed that *order judgment* and *quantity comparison* tasks recruited different processing mechanisms, as in the comparison task the distance effect emerged, while in the order task a reverse distance effect for pairs in ascending order (e.g., 3 5) has been described (Turconi et al., 2006). This pattern has been interpreted as evidence for a specific mechanism involved in order processing, that is, the serial search, indicating that judging quantity or order could imply the activation of the same magnitude representation but that different processing strategies are adopted on the basis of task demands or information activated by the stimulus.

In conclusion, these data seem to suggest that numbers are processed differently than other ordinal sequences, revealing the importance of understanding how non-numerical ordered sequences are processed, represented and activated in memory when information about relative position of stimuli is required to solve the task.

Chapter 2

HOW MUCH DO FINGERS COUNT? Directional biases in number-space association

1. Introduction

The assumption that cognition is fundamentally shaped by the interaction of the human body with its environment (e.g., Wilson, 2002; Gibbs, 2006) has provided new insights into different cognitive domains. Within the embodied cognition approach, finger counting has received a great deal of attention for being a sensory-motor behaviour fundamental to the development of numerical skills. The importance of finger counting consists not only in supporting informal arithmetic skills (Butterworth, 1999; Siegler & Shrager, 1984), but recent developmental studies have shown a correlation between finger gnosis, i.e., finger discrimination tasks, and arithmetic performance in school-aged children (Fayol et al., 1998; Noël, 2005; Gracia-Bafalluy & Noël, 2008).

Recently, several studies have suggested that finger counting strategies may even modulate the way numbers are mentally represented and influence their spatial association. For example, a cross-cultural study which compared hearing and deaf signing German subjects who use a two hands sub-base-five counting system with Chinese subjects who use a single hand semi-transparent number system (i.e., numbers above five are represented by symbolic finger configurations) demonstrated that the processing of Arabic numbers is strongly influenced by the structural system specific to finger counting habits (Domahs et al., 2010). In fact, in a magnitude comparison task number pairs with one number larger than five were responded to slower than would have been expected on the basis of their numerical distance alone, e.g., 4 and 6 yielded longer RTs than 6 and 8. This effect was culturally modulated, being reduced in Chinese subjects.

Furthermore, finger counting routines have been suggested to influence not only structural features of the mental numerical representation but also its spatial orientation. Particularly, the first hand used to count on fingers has been hypothesized to influence the typical stimulus-response compatibility effect observed in a number classification task (SNARC-effect; Fischer, 2008). In this study the number-to-finger preference assignment was evaluated by a written questionnaire in which Scottish participants (N = 550) were instructed to write numbers from 1 to 10 next to each drawn finger. According to the preferential direction of finger counting (i.e., the order in which hands are used to count on fingers) two subgroups of left-hand (N = 53) and right-hand (N = 47) starters were asked to perform a parity judgment task and results showed different SNARC effects, with only the former group presenting with a significant canonical left-to-right numerical mapping. These results suggest that the direction of finger counting partially shapes the spatial mapping of numbers at the representational level (Fischer, 2008) supporting the general idea of embodied numerosity. According to Fischer and Brugger (2011), finger counting could represent the initial determinant of spatial-numerical associations (i.e., the "*manumerical cognition*" approach), shaping especially the direction of these associations.

Another example of a modulation of the mapping of numbers on the representational space comes from a study in which Italian participants were asked to identify Arabic digits adopting all fingers according to different mappings, i.e., the finger counting mapping (small numbers counted on the right hand and large numbers counted on the left hand) vs. the SNARC-compatible mapping (small numbers associated to the left hand and large numbers associated to the right hand) (Di Luca et al., 2006). Participants were faster and more accurate when they responded using a mapping that was congruent with their own finger-counting than when they used the SNARC-compatible mapping (Di Luca et al., 2006). Similarly, an increase in muscle excitability in the right hand was recorded when judging small numbers (i.e., 1 to 4) compared to large numbers (i.e., 6 to 9) in right-hand counting starters, suggesting that adults' symbolic number processing is embodied by their finger counting strategy (Sato et al., 2007). However, when *embodied* (inherent in finger counting) and *disembodied* (extra-personal space) representations of numbers compete, the extra-personal spatial mapping seems to prevail, suggesting its primacy in numerical processing (Brozzoli et al., 2008), even if a very recent contribution showed that the spatial mapping between number magnitude and fingers is disembodied (i.e., magnitude-to-finger mapping is related to the position of fingers in space and not to their order on the hands; Plaisier & Smeets, 2011). However, this study may not exclude any embodied association, as no specific mappings between digits and fingers were considered (as well as in the study of Brozzoli and colleagues) and the range of numbers was larger than the number of fingers.

Yet, all these results suggest that the spatial representation of numbers seems to be modulated by the finger-digit mapping, determined by the finger counting practice. In particular, the structural features, especially the preferential direction, of the finger counting routine have been recently considered as a modulating factor in mapping numbers in space (Fischer, 2008). However, contrasting results have been recently reported with regards to the preferential direction of finger counting. For example, a large-scale questionnaire used to investigate finger counting patterns in a Scottish sample reported a stronger preference (66%) to start counting on the left hand (Fischer, 2008). On the contrary, a direct test of hand preference in Italian (Di Luca et al., 2006; Sato et al., 2007) and French (Sato & Lalain, 2008) populations revealed that most individuals preferred to start counting on their right hand (82% overall, 100% and 69% respectively). This difference can not be attributed to the reverse orientation of the reading-writing system (i.e., left-to-right vs. right-to-left) that might induce a visuo-spatial asymmetry due to the direction of scanning habits, commonly adopted to explain cultural discrepancies. Obviously these contradictory results may well be attributed to the different methods adopted to assess finger counting, that is via written questionnaire or via direct observation. All the more so, since the focus of attention is a motor routine, that is a spontaneous and overlearned practice, the possible gap between enacting and reporting about it is expected to be significant. Nevertheless, recently, the role of cross-cultural differences has been emphasised in a large-scale online survey (Lindemann et al., 2011) revealing a reversed preferential direction in Western (i.e., European and American) and Middle-Eastern (i.e., Iranian) populations. Most Western participants (68%) start counting preferentially on the left hand, while Middle-Eastern individuals reported a reversed pattern with a preference to start with the right hand (63%). This might suggest a role of the asymmetry in the scanning habits direction, but if the conventional scanning habit is a determinant of finger counting direction, intra-cultural differences should be minimal or absent. In contrast, this practice is not homogenous even within the same Western sample, since the left-starting preference is marked in Anglo-Saxon countries (i.e., UK, USA and Canada), but not in Belgians and Italians, partially confirming cultural effects but minimising the role of the writing system direction in predicting the starting preference.

All data collected thus far clearly indicate that finger counting habits may vary substantially both within and between cultures, suggesting that reading-writing system direction is not the only factor that modulates the starting hand preference during finger counting execution. Individual differences within the same population could be explained taking into consideration handedness which indeed shapes any other motor activities.

The hand preference is still an overlooked factor but it could potentially modulate the directional preference in counting routines. Indeed, when investigated, left-handers were found to be mainly left-starters, although the sample sizes of left- and right-handers were always strongly unbalanced. One of the few studies considering the link between handedness and finger counting direction indicated that French participants who started to count with their right hand showed higher right-hand preference in unimanual activities (Sato & Lalain, 2008). It worth noting that in this study only three left-handers were tested but, despite this highly unbalanced sample (i.e., 3 vs. 97), the left-handed individuals consistently started to count with the left-hand. A larger sample of left-handers (N = 76) was recently evaluated through the online survey (Lindemann et al., 2011), but in this case handedness was further qualified by cross-cultural differences. Indeed, the authors reported a more pronounced left-starting preference among Western left-handers (36/40, $p < .01$) but not within Middle Eastern left-handers ($p > .1$), possibly reflecting the interplay of both biological and cultural determinants in modelling finger counting practice.

A significant number of left-handed participants (N = 46) has been tested also in the Fischer's study (2008), revealing an absence of any influence on the finger counting direction, as indicated by the same proportion of left- and right-starters among left-handed. However, this result must be replicated controlling for any possible methodological confounds that reduce its ecological value. While enacting the motor routine involved an obvious implicit component, reporting on this practice via a written questionnaire requires the explicit access to finger counting representation.

It is evident that, besides the increased attention that finger counting has received for being a determinant factor in shaping number representation (Domahs et al., 2010; see also Domahs et al., 2011), a systematic analysis of the role of handedness in this practice is still missing.

The aim of the present study was to test whether the "*manumerical*" *cognition* hypothesis could explain the spatial-numerical associations. According to this theory, the counting preference would describe the directional SNARC effect, that is, individuals that prefer to start counting on the fingers of their left hand should show a left-to-right oriented mental numerical representation (easily associating small numbers counted on the left hand with left-sided responses), while on the contrary, who starts to count with the right hand should exhibit a right-to-left numerical mapping, or at least, a weaker spatial mapping (Fischer, 2008). In order to investigate this hypothesis a parity judgment task has been proposed to a left-starters (i.e., participants that started to count with their left-hand) and a right-starters (i.e., participants that started to count with their right hand) groups and the SNARC effect has been evaluated.

Another important goal of the study was to test the extent to which handedness predicts finger counting direction in Italian population. The finger counting practice has been assessed directly observing the subjects' motor action, supposing that a significant proportion of left-handers were left-starters and most of right-handers were right-starters. The first experiment consists of a substantial investigation on finger counting and montring (i.e., the way people show quantities with their fingers) habits in Italian population, focusing on the link between handedness and finger counting direction. The second experiment aims to explore possible differences in the SNARC effect showed in left- and right-starters.

2. Experiment 1: Handedness and Finger counting/montring

2.1 Method

One hundred sixteen students from the University of Milano-Bicocca, between the ages of 18 and 35 years (34 males; mean age: 22.7 years, SD: 4.06) participated in the present survey concerning their finger counting and montring habits. All participants were native Italian speakers and naive with regard to the hypotheses being tested.

2.1.1 Experiment 1a: Handedness assessment

All participants completed the *Edinburgh Handedness Inventory* (Oldfield, 1971), that asks whether they would use the left, right, or both hands to complete everyday activities (Fig. 2.1).

Edinburgh Handedness Inventory[1]

Your Initials:______________

Please indicate with a check (✓) your preference in using your left or right hand in the following tasks.

Where the preference is so strong you would never use the other hand, unless absolutely forced to, put two checks (✓✓).

If you are indifferent, put one check in each column (✓ | ✓).

Some of the activities require both hands. In these cases, the part of the task or object for which hand preference is wanted is indicated in parentheses.

Task / Object	Left Hand	Right Hand
1. Writing		
2. Drawing		
3. Throwing		
4. Scissors		
5. Toothbrush		
6. Knife (without fork)		
7. Spoon		
8. Broom (upper hand)		
9. Striking a Match (match)		
10. Opening a Box (lid)		
Total checks:	LH =	RH =
Cumulative Total	CT = LH + RH =	
Difference	D = RH – LH =	
Result	R = (D / CT) × 100 =	
Interpretation: (Left Handed: R < -40) (Ambidextrous: -40 ≤ R ≤ +40) (Right Handed: R > +40)		

[1] Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. Neuropsychololgia, 9, 97-113.

Fig. 2.1. The *Edinburgh Handedness Inventory* used to assess handedness.

2.1.2 Experiment 1b: Finger counting observation

In the finger counting task the experimenter asked participants to count from one to ten on their fingers. The only constraint was to keep their hands on their legs before starting to count. The examiner noted above drawing hands (Fig. 2.2) the finger-digit mapping adopted by each participant.

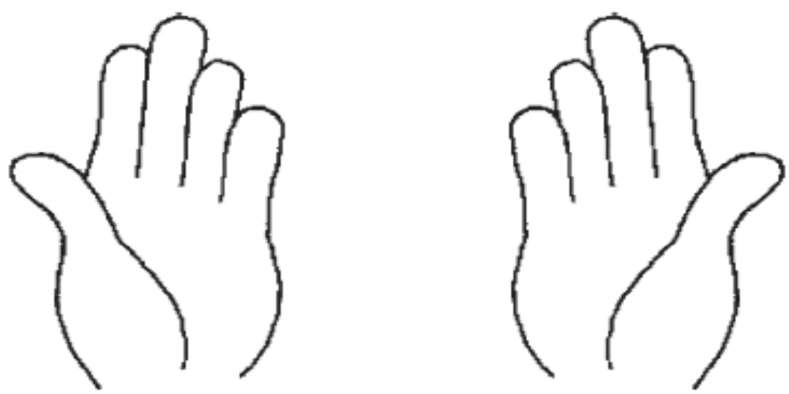

Fig. 2.2. Drawing hands used to note the finger counting mapping observed in each participant.

2.1.3 Experiment 1c: Montring observation

In the montring task the examiner asked to each participant to show how they express all numerosities from 1 to 9 using fingers and noted individual configurations (Fig. 2.3).

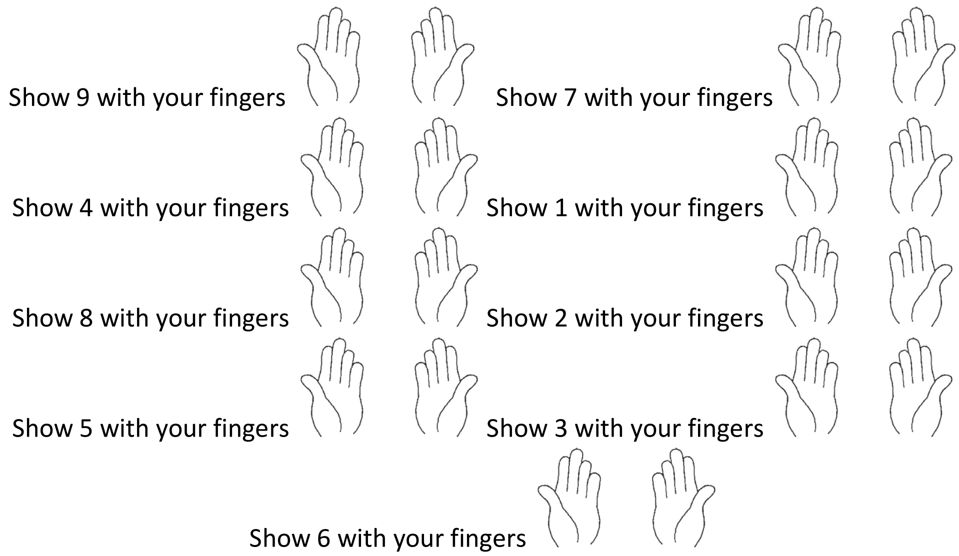

Fig. 2.3. Drawing hands used to note finger montring habits observed in each participant.

2.2 Results

2.2.1 Handedness assessment

A handedness score was calculated for each participant, dividing the difference between left and right preferences by the total number of responses and multiplying the result by 100. Participants were classified as left-handers if the score was below -40, as ambidextrous if the score was between -40 and +40, and as right-handers if the score was above +40. Thirty participants resulted left-handers (mean score -67.50, SD 16.92), sixty-three resulted right-handers (mean score 77.16, SD 17.29) and twenty-three participants were classified as ambidextrous (mean score 8.71, SD 30.56).

2.2.2. Finger counting

In line with typical Italian finger-digit mapping, all participants started to count with the thumb and proceeded to the little finger (with the left or the right hand) and continued with the same order (i.e., thumb, fore-middle-ring-little fingers) with the same or other hand. With regard to the first hand used, 60% of participants (70/116) started with the right hand and proceeded with the left, 33% (38/116) showed the opposite order, using first the left hand and then the right, and the remaining 7% (8/116) used only one hand, 5% (6/116) the right hand and 2% (2/116) the left.

2.2.3. Montring

Numerosities from 1 to 5 were represented by one hand only (with 1 to 5 fingers raised) in 78% (91/116) of participants, 53% (62/116) represented numbers from 1 to 5 using only the right hand and 25% (29/116) used only the left hand. All numbers were showed canonically (counting or montring configurations, Fig. 2.4) except for number 8, represented by montring configuration of number 4 on both hands in 10 participants. Specifically, number 1 was represented using canonical finger counting configuration in 82% (95/116) of participants and using montring configuration in the remaining 18% (21/116). Number 2 was represented by counting configuration in 16% (19/116) of participants and by montring configuration in 84% (97/116). Number 3 was showed using counting configuration in 98%

(114/116) of subjects and only 2% (2/116) used the montring one. Regarding number 4, 40% (46/116) of participants preferred counting configuration and 60% (70/116) the montring one. Numerosities from 6 to 10 were represented by the same finger configurations, with all the fingers on the other hand raised.

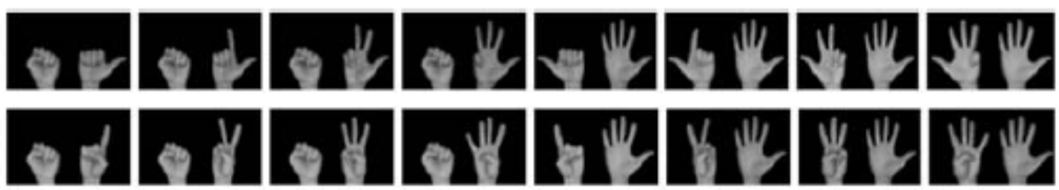

Fig. 2.4. Counting (above) and montring (below) configurations (from Di Luca & Pesenti, 2008)

Considering the relation between handedness and finger counting direction, 83% (25/30) of left-handers started counting with their left hand while only 13% (8/63) of the right-handers did so. By contrast, 87% (55/63) of the right-handers used their right hand first, while only 17% (5/30) of left-handers did so. The proportion of left and right-starters among left- and right-handers differed significantly, $\chi^2(1) = 44.29$, $p < .0001$.

Performance in the montring task corroborates these results showing 83% (25/30) of left-handers montring small numerosities using only the left hand, while only 5% (3/57) of the right-handers did so. On the contrary, 79% (45/57) of the right-handers used their right hand to show small numerosities, while only 10% (3/30) of left-handers did so. The remaining 13% (11/87) of left- and right-handers showed small numerosities using both hands. The proportion of participants that show small numerosities with left and right hand among left- and right-handers differed significantly, $\chi2(1) = 52.40$, $p < .0001$.

3. Experiment 2: Finger counting direction and numerical mapping

3.1 Participants

Based on the survey outcome, two groups of participants were selected based on their handedness, counting and montring direction to participate in the second study (i.e., left-handed left-starters, “left group”, LG [25 participants] and right-handed right-starters, “right group”, RG [25 participants]).

3.2 Procedure

The experiment consisted of a parity judgement task. Each participant sat in front of a computer monitor connected to a PC system running E-prime (Psychology Software Tools, Pittsburgh, PA, USA). Arabic numbers from 1 to 9 were presented, centred on the screen, in white on a black background. Participants were instructed to press the left (letter “A”) or the right (letter “L”) key on the keyboard to classify numbers as odd or even. Each participant completed the task performing both possible response mappings (i.e., left key for even numbers and right key for odd numbers and vice versa) in two separate blocks. The order of the assignment was counterbalanced across participants.

Each trial began with a fixation cross (500 ms) followed by a pause (500 ms), during which the screen was black. Then the target was displayed in 30-point Arial font, and remained on the screen until the participant's response. Afterwards, a black screen appeared for 500 msec. In both blocks each stimulus was presented ten times for a total of 180 stimuli, the order of which was randomized for each participant. Each block started with nine training trials which were removed prior to data analysis. Instructions emphasized both speed and accuracy.

3.3 Results

To improve the internal validity of the study, RTs greater than 3SD above the group mean, calculated separately for left- and right-hand responses and for LG and RG, were discarded. Accordingly, 4.6% and 5.8% of the trials were eliminated for the LG and RG respectively.

To investigate the SNARC effect, a regression analysis for repeated measures data was applied (Lorch & Myers, 1990, method 3; see also Fias et al., 1996). From the association between numbers and space, a negative relation between magnitude and dRT is predicted: if small numbers are associated with left, responses will be faster with the left hand, resulting in a positive dRT, whereas negative dRTs are expected for large numbers. In a first step, for all participants the mean RT of the correct responses was computed for each number, separately for left and right responses. On the basis of these mean RTs, dRTs were computed by subtracting the RT for left-hand responses from the RT for right-hand responses. In a second step, for each individual participant, a regression analysis was computed with the magnitude as the predictor variable. In a third step, one-tailed t-tests were performed to test whether the regression weights of the group deviated significantly from zero.

The overall regression weight was -8.98 ms/digit for LG (SD 8.80, range -24.7 to + 10.9), $t(24) = -5.100$, $p < .0001$ (88% [22/25] of the subjects showed a negative slope) (Fig. 2.5), and -8.29 ms/digit for RG (SD 4.97, range -15.2 to + 2.3), $t(24) = -8.347$, $p < .0001$ (92% [23/25] of the subjects showed a negative slope) (Fig. 2.6), revealing a significant SNARC effect in both groups.

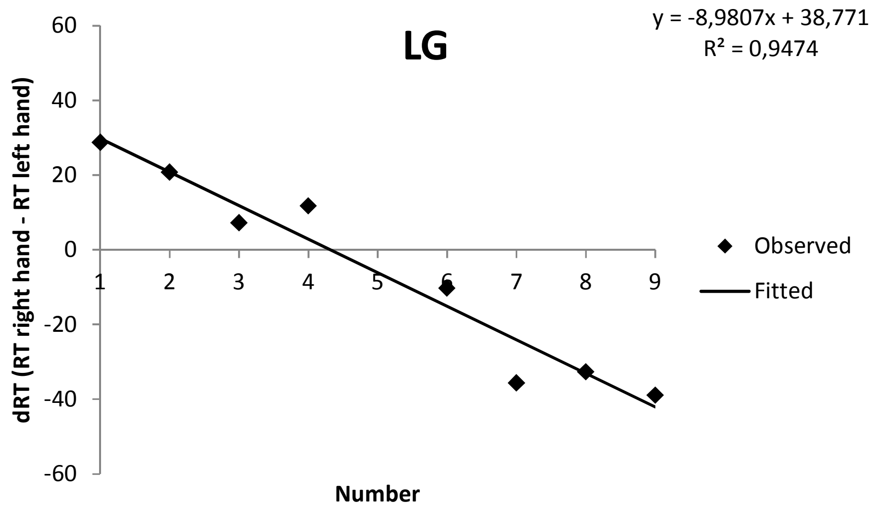

Fig. 2.5. RT differences between right-handed and left-handed responses as a function of numerical magnitude in the Left Group.

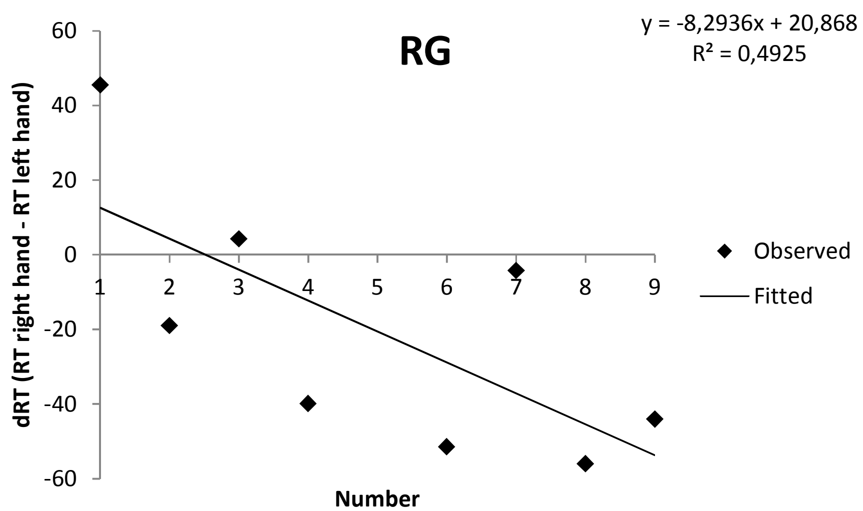

Fig. 2.6. RT differences between right-handed and left-handed responses as a function of numerical magnitude in the Right Group.

In particular, the general regression fits for LG and RG (Figure 2.5 and Figure 2.6) reveal that the classical SNARC model accounts for 95% of the variance in LG and for 49% of the variance in RG. However, comparing the individual slopes in LG and RG revealed that the two groups did not differ, $t(48) = 0.34$, $p = .73$. Moreover, as depicted in Figure 2.7, variability of slopes is significantly lower in RG than in LG (Levene's test, $F[1,48] = 6.51$, $p < .05$); yet, even when adjusting the degrees of freedom for unequal variance, the groups' slopes did not differ, $t(37.88) = 0.34$, $p = .74$

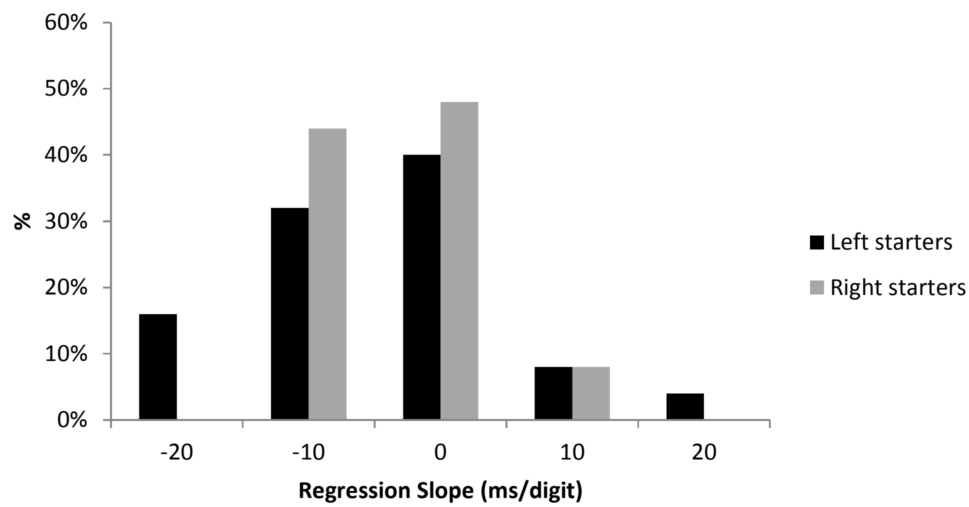

Fig. 2.7. Distribution of regression slopes in left- and right-starters. Labels indicate upper decades limits.

4. Discussion

The present study has been conducted in order to investigate whether the spatial numerical mapping was influenced by the finger counting routine, as the *manumerical cognition* hypothesis states (Fischer, 2008). In doing so, this study allowed to further explore the finger counting and montring habits of Italian population, the link between handedness and finger counting direction and the potential influence of the latter on the SNARC effect.

First of all, Italian participants displayed a typical finger counting procedure consisting in the consecutive use of both hands with the sequential involvement of all fingers (i.e., from thumb to little finger) (Di Luca et al., 2006; Sato et al., 2007; Sato & Lalain, 2008). On the basis of previous cross-cultural studies, number-digit mapping seems to be related to cultural factors, such as the writing system direction (i.e., left-to-right vs. right-to-left), since Iranian subjects adopt a reverse order (i.e., from little finger to thumb) (Lindemann et al., 2011). Even regarding montring habits, all participants represented numerosities using canonical configurations (Di Luca & Pesenti, 2008).

More critically, results showed that handedness influences the direction of the counting procedure, with left-handers mostly starting with their left hand, and right-handers primarily starting with their right hand. Although this pattern of results is not new, previous studies reporting both handedness and direction of finger counting based their observation on a strongly unbalanced sample size of left and right handers (Sato & Lalain, 2008; Lindemann et al., 2011). A single study testing a larger sample of left- and right-handers failed to report any correlation between handedness and first hand used for counting (Fischer, 2008), although a recent online survey reported a more pronounced left-starting preference among left-handers (Lindemann et al., 2011). Overall, it is not possible to exclude that the collection procedure, i.e., written questionnaire, might have influenced the results, inducing, for example, an overestimation of the left-to-right finger-digit-mapping consistent with the dominant writing system. In fact, when counting performance was directly accessed, similarly to the current study, handedness fully accounts for finger counting direction (Sato & Lalain, 2008). Due to the low proportion of left-handers in the population, only cumulative data from finger counting performance will provide definitive evidence on the role of handedness in finger counting habits.

The main purpose of the study was to test the hypothesis that finger counting habits contribute to the mapping of numbers in the representational space (Fischer, 2008). According to this hypothesis, the number-space association, as indexed by the SNARC effect, should be consistent with the number-finger association, as indexed by finger counting routines (Fischer, 2008). Results clearly show that a highly significant and continuous left-to-right SNARC effect characterizes the performance of both left-starters (left-handers) and right-starters (right-handers): within an overall advantage for the dominant hand in right-handers, the numerical magnitude modulates the extent to which a lateralised response was preferentially associated to a specific stimulus, independently of finger counting direction or handedness.

These results suggest that the embodied number-space association built up from finger counting routines (e.g., Fischer & Brugger, 2011) does not obligatory shape the spatial mapping of numbers at the representational level. Additional caution is merited given the recent observations of the reduced use of fingers in blind children (Crollen et al., 2011) despite similar SNARC effects in both blind and sighted adults (Castronovo & Seron, 2007; Sallilas et al., 2009) and the discrepancy between finger counting direction and directional biases in processing numerical information in preschool children (Girelli et al., 2011). On these grounds, although it is unquestionable that multiple numerical spatial mappings, *embodied* (finger counting) and *disembodied* (e.g., rulers), do coexist and can be flexibly used depending on the context (Di Luca et al., 2006; Brozzoli et al., 2008), further studies are needed to improve our understanding of the way in which they interact. In particular, it still remains to be explored how the spatial mapping of numbers is determined and which factors might influence the organisation of these spatial associations.

Chapter 3

Placing order in space: the SNARC effect in serial learning

1. Introduction

The spatial organization of the mental number representation has received much consideration in the last decades (for a review see Fias & Fischer, 2005), since the hypothesis that numbers are represented on an imagined oriented line has been published (Dehaene et al., 1993). According to it, increasing magnitudes are mentally represented as spatially ordered from left to right. The strongest support for this hypothesis comes from the SNARC effect (Spatial Numerical Association of Response Codes [Dehaene et al., 1993]), according to which small numbers elicit faster left-side responses while large numbers evoke faster right-side responses. As described in the previous chapter, the spatially coded representation does not depend either on handedness (Dehaene et al., 1993; Müller & Schwarz, 2007), or on finger counting direction, while cultural factors such as the direction of the writing system appear to be critical (Shaki & Fischer, 2008; but see Shaki & Gevers, 2011).

Interestingly, in most of reported studies supporting a spatially organized mental representation of numbers the numerical value is irrelevant to the task, indicating that the SNARC effect is elicited by the automatic activation of this magnitude representation (Dehaene et al., 1993; Fias et al., 1996; Fischer et al., 2003). Another effect characterising number comparison is the distance effect, namely longer reaction times to stimuli closer to the reference (i.e., comparing 4 and 5) than to stimuli further apart (i.e., comparing 5 and 9) (Moyer & Landauer, 1967). This phenomenon has been interpreted as evidence for a mental oriented representation along which numbers are represented as a Gaussian distribution that overlaps more for numerically close numbers (Piazza et al., 2004). Recently, however, comparison distance effect has been explained without assuming the characteristics commonly attributed to the mental number line (Verguts et al., 2005) and alternative accounts have been proposed (Gevers et al., 2006; see chapter 1).

Importantly, it has been recently reported that different non-numerical magnitudes show spatial stimulus-response compatibility effects (e.g., the SNARC effect). In fact, quantitative dimensions such as time (Ishihara et al., 2008) and pitch (Rusconi et al., 2006), which are intrinsically ordered, elicit faster left-side responses to early onset timing and low-frequency pitches and faster right-side responses to late onsets and high-frequency pitches, indicating a congruency effect comparable to the SNARC effect.

More critically, a spatial compatibility effect has been reported also for overlearned, non-quantitative sequences such as letters, days and months (Gevers et al., 2003; 2004). In these studies, the spatial coding corresponds to the association of the elements at the beginning of the series with ‘left’, and the elements at the end of the series with ‘right’. Note that this stimulus–response compatibility occurs in both order-relevant (e.g. “Does Monday come before or after Wednesday?”) and order-irrelevant (e.g. “Does November end in R?”) tasks. Moreover, similar to the numerical comparison, the classification of ordinal series elicits a standard distance effect. These results suggest that the mental representation of a non-numerical ordinal sequence is spatially coded and this spatial component is automatically activated.

Furthermore, evidence for shared mechanisms for quantity and order coding comes from neuroimaging studies. The intraparietal sulcus is equally activated in the comparison of numbers and letters, suggesting its role in the representation and processing of numerical (Dehaene et al., 2003) and non-numerical ordinal series (Fias et al., 2007; Marshuetz et al., 2000). However, some behavioural effects do not seem to apply to the same extent to numerical and non-numerical information (Zorzi et al., 2006; Dodd et al., 2008), yet these differences may well be attributed to differences in processing (Dodd et al., 2008) rather than in the mental representation.

To sum up, the evidence so far suggests that the representation of ordered series, whether numerical or not, shares the common feature to be spatially organized. Although the specific direction of this representation may be culturally determined, a spatial representation may constitute the privileged way of mentally organizing serial information. Clearly, numbers and letters are highly practiced sequences, but it might well be that is the ordinal information to be mapped in the representational space. Preliminary evidence in support of this hypothesis has been recently reported in an fMRI study where a SNARC effect was observed for an extensively trained arbitrary ordered sequence of abstract figures. Critically, the effect was limited to order-relevant task (Van Opstal et al., 2009).

To test the hypothesis that the ordinal meaning constitutes the hint for mapping sets of elements onto spatial positions, the present study investigates whether a spatial coding occurs for a newly learned ordered sequence of words/images. If learning a list of words induces a spatial organization of the elements, then a word position-response compatibility effect (analogous to the SNARC effect) might be obtained, as well as a distance effect. In line with previous studies, both order-relevant and order-irrelevant tasks were adopted. The presence of the SNARC and the distance effects in order-relevant tasks will be considered indexes of a spatial mental representation of the newly acquired series, whereas their occurrence in an order-irrelevant task will allow to highlight automatic activation of this representation. This automatic activation will be further tested by a target detection task, investigating whether the irrelevant presentation of over-learned stimuli could influence the allocation of attention, similarly to the attentional SNARC effect (Fischer et al., 2003).

2. Experimental

2.1 General method

2.1.1 Participants

Seventy-three right-handed Psychology students from the University of Milano-Bicocca, aged between 19 and 28 years (61 females; mean age, 22.6 years) volunteered to participate for course credits. Twenty of them participated at the word-classification order task, sixteen at the image-classification order task, eighteen participated at the letter-detection task and nineteen at the stimuli-detection task. All subjects were naive about the purpose of the experiment and the hypotheses being tested.

2.1.2 Stimuli

Nine four- and five-letter words were selected to be phonologically and semantically different and ordered in the following list: “arco” (bow), “tenda” (tent), “mela” (apple), “treno” (train), “sedia” (chair), “rosa” (rose), “faro” (lighthouse), “gatto” (cat) and “palma” (palm) (Fig. 3.1). For each word, the corresponding image was identified from the PD/DPSS database (Lotto et al., 2001). Each spoken word was recorded to be presented auditorily via computer when appropriate. A computer monitor connected to a PC system running E-prime (Psychology Software Tools, Pittsburgh, PA, USA) was used to present stimuli and record subjects' responses. White stimuli (words or images) were presented in the centre of the monitor against a grey background. Written words were displayed in Arial font, bold style, 30 points in size.

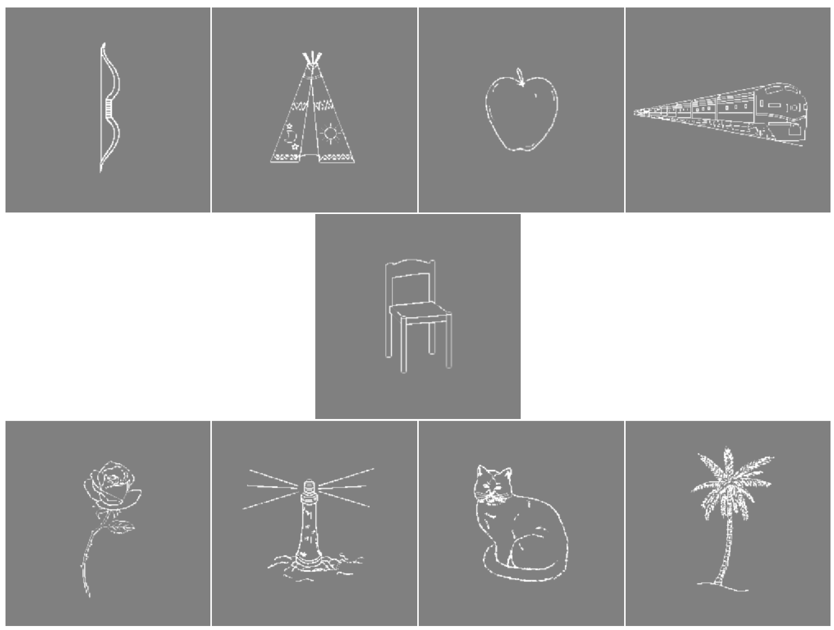

Fig. 3.1. Images used as stimuli in the learning, the figure classification and the detection tasks.

2.1.3 Procedure

2.1.3.1 Learning

Subjects learned the list of nine words through both visual and auditory presentations. The learning phase consisted of three parts: in the first part, words were presented auditorily in a fixed order for three times, while the corresponding images and the corresponding written words appeared concurrently at the centre of the screen. Each word appeared every 2 s. In the second part, only images and auditory words were presented, again three times. In the third part, subjects were told to repeat the words while the corresponding images were presented in the fixed order, three times. After each part was completed, subjects were asked to repeat aloud the sequence. After learning the list, subjects underwent a training phase aimed at strengthening the memory for the positions of each word within the list.

2.1.3.2 Training

In a first task, subjects saw a triplet of words, horizontally displayed, with one word missing and replaced with an empty space, and they had to name aloud the missing word using a microphone. In a second task, subjects had to say the word that followed the one visually presented ("What comes next?"), and in a third task, the word that preceded it ("What comes before?"). Order of presentation was the same for all participants and instructions were written on the screen at the beginning of the tasks. Since each of the nine words in the list was verified three times in each training task, the single task had 27 stimuli. A trial began with a central fixation point (500 ms), and after 500 ms (blank), the triplet appeared centred on the screen, and remained visible until the subjects' response. In all tasks, feedback was provided although no self-corrections were allowed. At the end of the training phase, subjects were told to repeat aloud the list twice.

2.1.3.3 Experiments 3, 4 and 5: Classification tasks

Subjects were randomly assigned to one of three classification tasks (two of them were order-relevant and a third one was order-irrelevant) or the target detection task. In the *written word before/after classification task,* subjects had to decide whether the word visually presented came before or after the middle one ‘chair’. The *figure before/after classification task* was identical to the previous one, but images were displayed instead of words. The same figures were used in the *phoneme monitoring task*, where subjects had to decide whether an “R” does belong or not to the name of the image. In all tasks, subjects responded by pressing one of two response keys, and the left/right-hand key assignment was reversed in a second block of trials. This order was counterbalanced across participants. In every task, each stimulus was presented twenty times for a total of 160 stimuli presented in two separated blocks. The order of stimuli presentation within each block was randomized for each participant. A trial began with a central fixation point that remained on the screen for 500 msec. After a 500-ms blank, the target stimulus (word or figure) appeared and its presentation was terminated by the subject’s response (Fig. 3.2). Each block started with eight training trials, not further analysed. Each experiment lasted approximately 15 min.

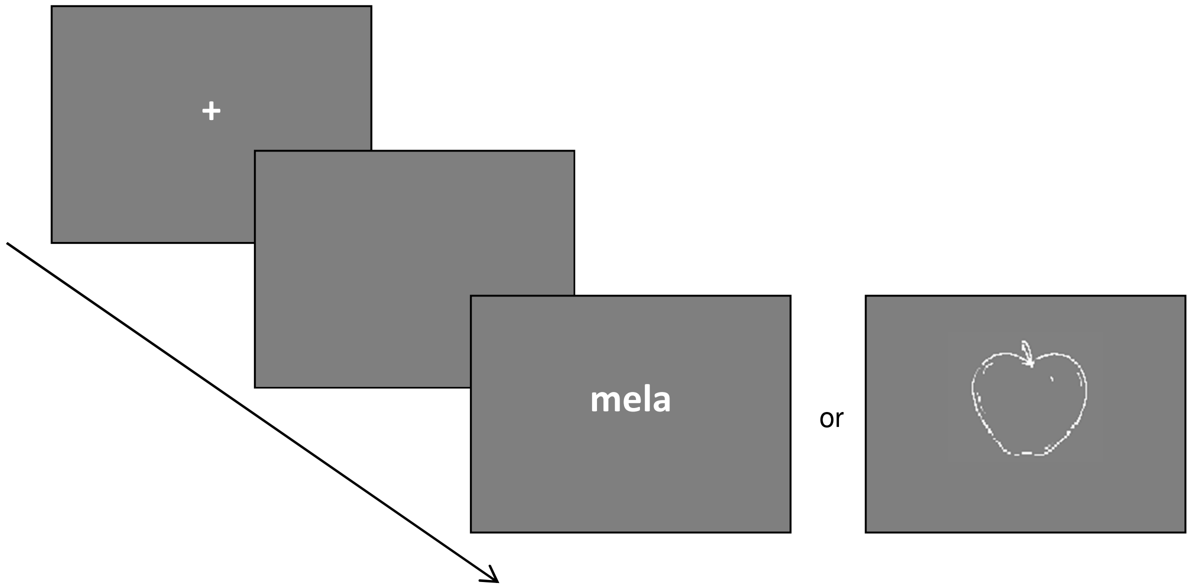

Fig. 3.2. Trial sequence of classification tasks.

2.1.3.4 Experiment 6: Target detection task

Participants performed a *target detection task* with their head positioned on a chin rest. They were instructed to fixate a white cross that was 0.2° in diameter and centred between two squares (each had 4° side). After 500 ms one of the memorized images appeared for 300 ms and participants knew that each image was irrelevant for the task. After a delay of 500 ms or 750 ms, a target word corresponding to the image presented before appeared in one of the two boxes and participants had to press the space bar as soon as they detected the target (Fig. 3.3). Only the first (i.e., “arco”), the second (i.e., “tenda”), the fifth (i.e., “sedia”), the eighth (i.e., “gatto”) and the ninth (i.e., “palma”) stimuli were displayed, in order to improve the potential shift of attention due to the most extreme positions in the memorized list. Each stimulus was presented 76 times, 32 times for each side and 12 times no target appeared in the boxes in order to prevent anticipatory responses, for a total of 380 stimuli. Instructions emphasized both speed and accuracy.

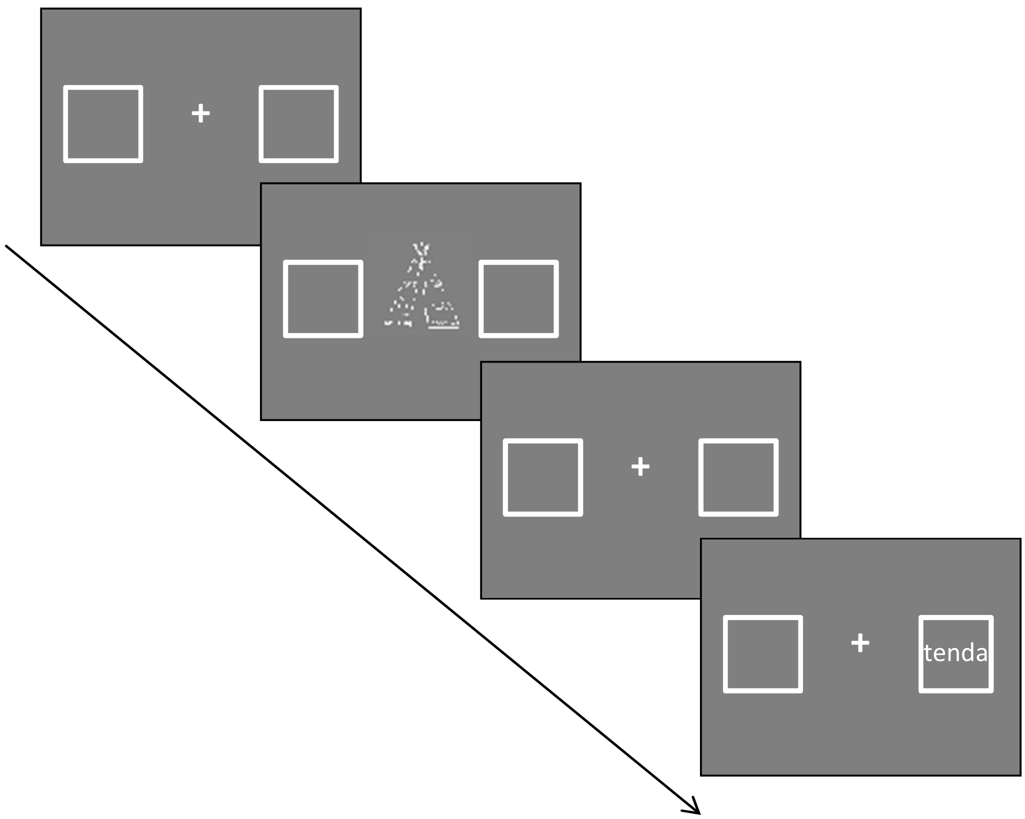

Fig. 3.3. Trial sequence of target detection task

The study was run in three different sessions during the same week in order to improve consolidation of the list in memory. During the first and second sessions subjects performed learning and training tasks and, during the third one, they were presented with a classification or the detection tasks, after having rehearsed aloud the list three times.

2.2 Results

2.2.1 Learning and training

Half of the subjects repeated correctly the list after the first part of the learning phase, 30.0% after the second part, 5.0% after the third, and the remaining 15.0% after training tasks. In the first training task the overall error rate was 14.6%; for the “What comes next?” task the error was 13.5%, and for the “What comes before?” task it was 11.6%.

2.2.2 Experiment 3: Written-word classification task

2.2.2.1 RT analysis

To improve the internal validity of the study, in all experiments RTs below 250 ms and RTs 3SD above the overall group mean, calculated separately for left- and right-hand responses, were discarded. Accordingly, 6.8% of the trials were eliminated in the written-word classification task. The overall median RTs for the target words from the first to the ninth positions (except fifth) were, respectively 636 (SD = 205), 692 (SD = 210), 680 (SD =

228), 719 (SD = 237), 747 (SD = 245), 709 (SD = 242), 686 (SD = 233), and 671 (SD = 203) ms.

To investigate the position x side of response interaction, a regression analysis for repeated measures data was applied (Lorch & Myers, 1990; see Chapter 2 for details). The t-test performed to test whether the regression weights calculated per subject with position as predictor variable on dRTs reached significance, as dRTs decreased with 8.71 ms per position [$t(19) = -1.681$, $p = .05$]. In fact, left-hand responses were faster than right-hand responses for the first four positions (622, 682, 674, and 710 ms vs. 649, 695, 681, and 728 ms, respectively) and right-hand responses were faster than left-hand responses for the last four positions (735, 695, 667, and 650 ms vs. 760, 718, 700, and 690 ms, respectively) (Fig. 3.4).

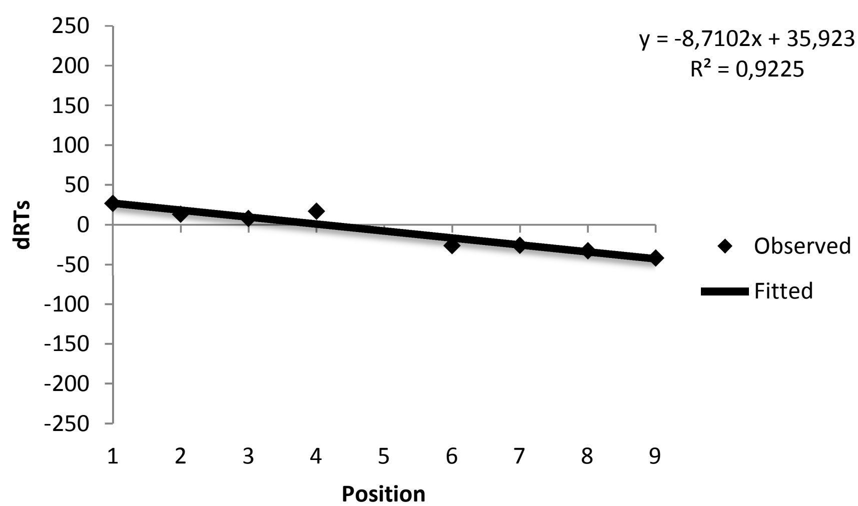

Fig. 3.4. RT differences between right-handed and left-handed responses as a function of word position in the written-word classification task.

The regression analysis was conducted also with *distance* from the reference word (i.e. chair) as predictor variable for each subject, and the regression slope deviated significantly from zero [$t(19) = -7.632$, $p < .0001$]. In fact, responses were faster when the distance from the reference to the target was large than when it was smaller (distance 1 = 731 ms, distance 2 = 694 ms, distance 3 = 688 ms, and distance 4 = 652 ms).

2.2.2.2 Error analysis

The average error rate was 3.3%. The regression analysis carried out on accuracy data did not indicate any preferred lateralised response key as a function of the position of the word [$t(18) = 1.071$, $p = .1$]. However, the regression analysis with distance as predictor variable deviated significantly from zero [$t(18) = -2.363$, $p < .05$], indicating that the error proportion was larger when the target was closer to the reference than when it was further apart.

2.2.3 Experiment 4: Image-classification task

2.2.3.1 RT analysis

The trimming of data eliminated 4.8% of trials. The overall median RTs for the target images from the first to the ninth positions (except fifth) were 683 (SD = 336), 710 (SD = 335), 734 (SD = 301), 804 (SD = 377), 813 (SD =

354), 815 (SD = 399), 729 (SD = 319), and 701 (SD = 323) ms, respectively. Median correct RTs were computed for each target, each side of response, and each subject. Regression analysis highlighted an association between position in the ordered sequence and side of response, as dRTs decreased with 51.97 ms per position [$t(15) = -4.22$, $p < .0001$], specifically left-handed responses were faster than right-handed responses for the first four positions (608, 624, 662, and 744 ms vs. 758, 796, 806, and 864 ms, respectively) and right-handed responses were faster than left-handed responses for the last four positions (708, 728, 655, and 627 ms vs. 917, 903, 803, and 776 ms, respectively) (Fig. 3.5).

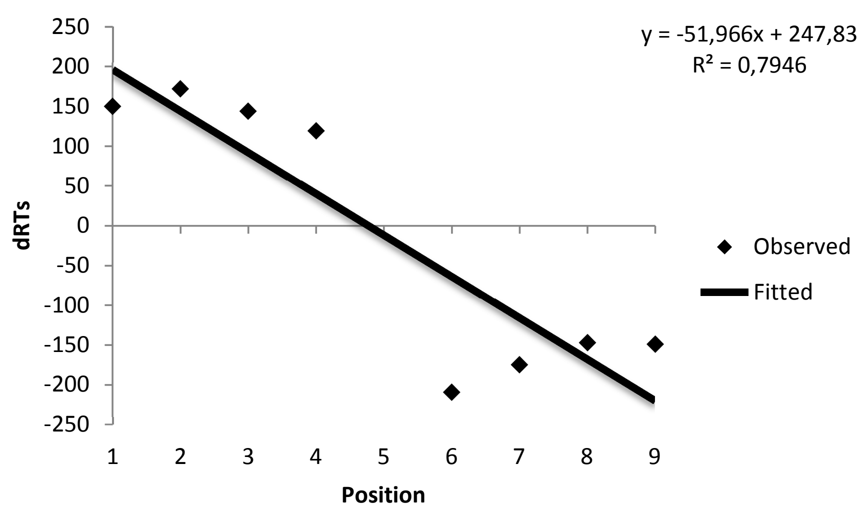

Fig. 3.5. RT differences between right-handed and left-handed responses as a function of word position in the image-classification task.

The regression analysis with *distance* from the reference word (i.e. chair) as the predictor variable deviated significantly from zero [$t(15) = -5.045$, $p < .0001$]. Responses were faster when the distance from the reference to the target was large than when it was smaller (distance 1 = 802 ms, distance 2 = 770 ms, distance 3 = 718 ms, and distance 4 = 691 ms).

2.2.3.2 Error analysis

The average error rate was 3.1%. The regression analysis on errors' proportion revealed that the stimuli position within the list was a good predictor of the preferred side of response [$t(15) = 2.745$, $p = .01$]. However, regression analysis with distance from the reference as predictor variable of error frequency failed to reach significance [$t(14) = -1.340$, $p = .1$].

2.2.4 Experiment 5: Letter-detection task

2.2.4.1 RT analysis

The trimming procedure eliminated 3.7% of trials. The overall median RTs for the target images from the first to the ninth positions (except fifth) were 571 (SD = 164), 616 (SD = 162), 609 (SD = 158), 575 (SD = 156), 570 (SD = 180), 564 (SD = 153), 630 (SD = 172), and 610 (SD = 167) ms, respectively. Median correct RTs were computed for each target, each side of response, and each subject. Regression analysis with position of the stimulus as the predictor on the preferred side of response resulted significant, as dRTs decreased with 4.93 ms per position [$t(17) = -1.580$, $p < .05$]: although right-handed responses were overall faster than left-handed responses, this advantage was modulated by the relative position of the stimulus, yielding a reduced but significant SNARC effect (first four positions, left-hand 564, 632, 610, and 574 ms vs. right-hand 582 601, 608, and 577 ms; last four positions, left-hand 573, 589, 642, and 628 ms vs. right-hand 567, 540, 620, and 592 ms) (Fig. 3.6).

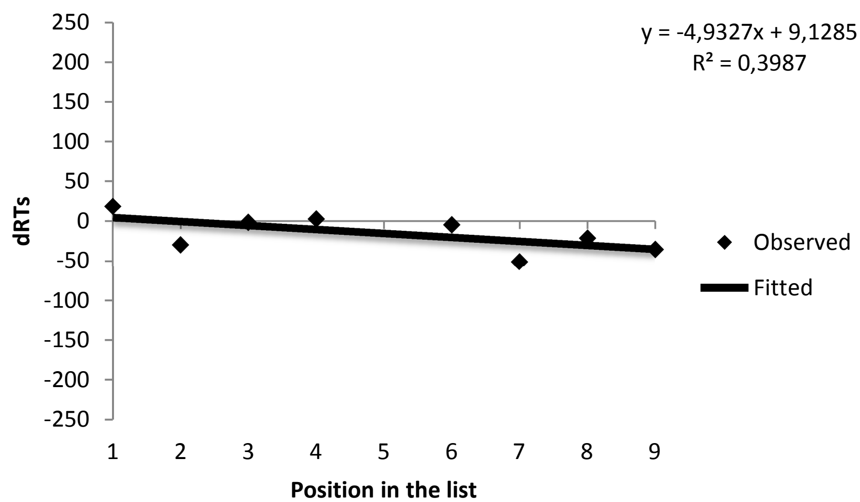

Fig. 3.6. RT differences between right-handed and left-handed responses as a function of word position in the letter-detection task.

2.2.4.2 Error analysis

The average error rate was 2.5%. Regression analysis with position of the stimulus as predictor of the relative error frequency on right- and left-handed responses resulted significant [$t(16) = 4.157$, $p < .001$]. Finally, we compared the individual regression slopes across the tasks and we obtained a significant divergence between image-classification and letter-detection tasks ($t[32] = -3.953$, $p < .001$) as well as between image-classification and word-classification tasks ($t[34] = 3.484$, $p < .01$), while word-classification and letter-detection tasks did not differ ($t[36] = -0.632$, $p = .53$).

2.2.5 Experiment 6: Target detection task

Average reaction time was 305 ms (SD = 179 ms) and the average error rate detecting the target was 1.15% (SD = 1.02%). For each participant, median RTs were computed and subjected to a 2 x 2 x 2 repeated measures ANOVA with *delay* (500 vs. 750), *position* of the stimulus in the list (first two vs. last two) and *side* in which targets appeared (left vs. right) as within subject variables. The ANOVA revealed only a main effect of delay ($F[1, 18] = 14.369$, $p < .01$), indicating faster responses (351 ms) when the delay was longer (750 ms) compared to the responses (365 ms) when the delay was shorter (500 ms). The position of stimuli in the list was not significant ($F < 1$) and the side in which targets appeared was marginally significant ($F[1, 18] = 3.526$, $p = .08$), as right-sided targets were detected faster (354 ms) than left-sided target (362 ms). Importantly, the interaction between the ordinal position of stimuli in the list and side was not significant ($F < 1$), as well as the other interactions ($p > .1$) (Fig. 3.7).

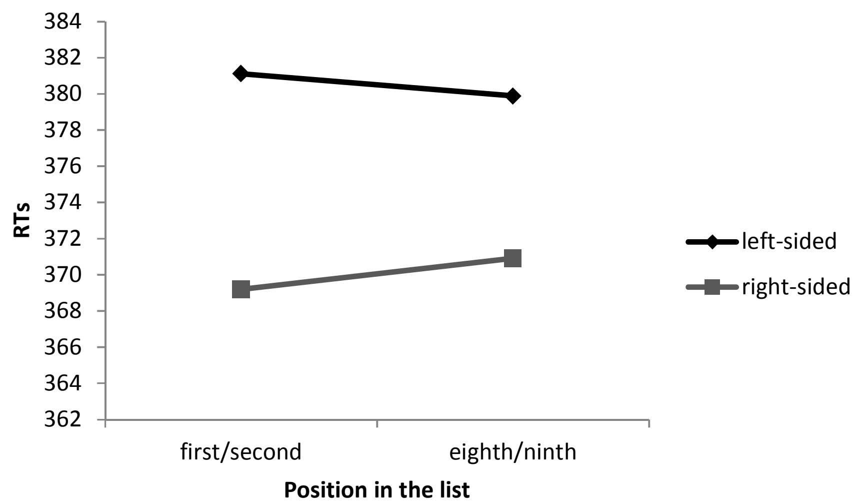

Fig. 3.7. Average reaction times (RTs) to firsts and lasts positions.

3. Discussion

The purpose of the present study was to establish whether a newly learned ordered sequence of words would convey a spatial coding, suggesting that this information may be mapped in the representational space, as for other overlearned sequences (i.e., numbers, months, days of the week; Dehaene et al., 1993; Gevers et al., 2003; 2004). According to numerical cognition literature, the SNARC and the distance effects have been considered as indexes for the spatial nature of the mental representation.

In the first task (Experiment 3), where subjects had to classify written words, stimuli at the beginning of the list were responded to faster with the left than with the right hand, whereas words at the end of the list were responded to faster with the right than the left-hand, mimicking the standard SNARC effect. Furthermore, the presence of a clear-cut distance effect confirms that the newly acquired discrete information was spatially distributed along a mental representation. Although the distance effect may partially derive by a well-known memory phenomenon by which stimuli in the first (primacy effect) and the last positions (recency effect) within a list are better remembered (Atkinson & Shiffrin, 1968), the response-side preference unequivocally indexes a spatial mapping. The same pattern of results was obtained with the image-classification task (Experiment 4), strengthening the hypothesis of a spatial mental representation of newly acquired series oriented from left to right regardless of the stimulus format.

Finally, and most important, in the letter-detection task (Experiment 5) the significant interaction between the position of the stimulus and the response side indicates that the spatial feature of the word list was indeed activated in an automatic way, since order information was irrelevant to the task. The comparison of the regression slopes across the tasks indicates a larger effect for image classification. While the larger effect in the image-classification task (Experiment 4) compared to letter detection (Experiment 5) is well expected (as in Gevers et al., 2003), the difference between word

(Experiment 3) and image classification is less obvious. One possible explanation comes from the fact that images are repeated more frequently than words in the learning phase, possibly strengthening their association to an internal ordered representation. Furthermore, the larger SNARC effect in image classification may also reflect the well-known asymmetry in picture and word processing due to the pictures advantage in accessing semantic representation (e.g., Glaser, 1992). Additionally, this finding applies also to the numerical domain where a systematic difference between Arabic digits and number words is reported in reading (e.g., Damian, 2004), stroop-like tasks (Fias et al., 2001b) and SNARC-related paradigms (Dehaene et al., 1993; Nuerk et al., 2004). Overall, these results indicate that previously reported associations between overlearned ordinal sequences (e.g., numbers and letters of the alphabet) and spatial codes extend to newly acquired ordered sequences. This suggests that the use of a spatial medium for representing order is mandatory and routinely used, allowing for the preservation of the order embedded in the series. In fact, the observed stimulus–response compatibility effect and the distance effect suggest that a newly memorized series is mentally represented along a left-to-right spatial medium, similar to well-established and/or more salient ordinal strings (Dehaene et al., 1993; Gevers et al., 2003, 2004). Accordingly, this study suggests that a left-to-right spatial arrangement of information in long-term memory is the preferential way to organize ordinal learning, at least in the western cultures, whether or not this organization results from a strategic mapping of ordered elements in the space (Fischer, 2006).

The last experiment (Experiment 6) aimed to determine whether centrally presented stimuli conveying ordinal information would influence the attention allocation during a target detection task. Apart from the classical finding that mean reaction time decreases as SOA increases (i.e., foreperiod effect), no interaction between position of the stimuli in the sequence and side of target detection emerged. This attentional SNARC has been reported in previous researches (Fischer et al., 2003; Dodd et al., 2008), showing that left target detection was facilitated when a small number was presented before and the opposite (i.e., presentation of large number) was true for right target detection. These results were replicated with letters/days/months as stimuli, but only when participants were required to actively process stimuli in an order-relevant manner (Dodd et al., 2008). This suggests that some processing mechanisms (i.e., automatic allocation of spatial attention) are specific to numbers, since numerical and non-numerical series are critically different in terms of familiarity and salience of the ordinal information (i.e., order is intrinsic to numbers and not to any other sequence). However, it has been recently shown that even the number-mediated orienting is not obligatory and produces weaker and slower effects than other symbolic cues, such as eye-gaze or words “left” and “right”, that convey a fixed, unambiguous, directional meaning (Hommel et al., 2001; Galfano et al., 2006).

In conclusion, this study adds to previous evidence for the spatial organization of newly acquired ordered information (Van Opstal et al., 2009), and extends this finding showing, for the first time, the automatic access to this representation. Thus, a visuo-spatial internal representation seems to reflect the spontaneous spatial mapping of ordered information, independent of its nature. In particular, a mental spatial coding takes place even for information that is newly acquired and that does not convey either magnitude or intrinsic ordinal meaning.

Chapter 4

The role of Working Memory in number processing

1. Introduction

The previous chapters have explored to what extent the origin of spatial associations characterizing numerical information depends on finger counting direction or arises from a systematic mapping established when ordinal sequences are organized in memory. The results of Chapter 2 show that finger counting direction, as well as the handedness, has no influence on the direction of the mental spatial representation of numbers. Alternatively, in Chapter 3 the presence of spatial associations, i.e., the SNARC and the distance effects, evoked by a newly memorized list of elements, suggests that it could be order, and not magnitude, the crucial determinant of spatial numerical associations. Therefore, the long-term mental representation of magnitude (i.e., the *mental number line*) might not be the (only) factor that explains the occurrence of spatial phenomena like the SNARC effect as it has been classically conceived (Dehaene et al., 1993; for a review, see Fias & Fischer, 2005). Indeed, several reports revealed that the number-space association is not so stable as it would be expected being magnitude conceptualized as a long-term memory representation. For example, a reversed numerical spatial congruency effect has been obtained when participants practiced incompatible mapping rules (Notebaert et al., 2006), indicating that the number-response side compatibility is not absolutely determined. This flexibility was already signalled by the reported range/context dependency, according to which the association between a number and the left or right response-side depends on the range in which numbers occur in the specific task (Dehaene et al., 1993) and on the mentally imagery of stimuli (Bachtold et al., 1998). In fact, considering for example numbers 4 and 5, a faster left response emerged when numbers task-set ranged between 4 and 9, while a faster right response was elicited when the task-set ranged from 1 to 5 (Dehaene et al., 1993; Fias et al., 1996). Furthermore, when subjects were asked to imagine numbers on a clock face (i.e., small numbers are displayed on the right side and larger numbers on the left side) the SNARC effect reversed (Bachtold et al., 1998).

Additional evidence comes from the studies on bilingual participants, reporting a modulation of the number-space association due to both the direction of the text read before the numerical task (Shaki & Fischer, 2008) and the spatially location of numbers on the left or the right of text lines during reading (Fischer et al., 2010).

All these results clearly highlight that the spatial coding of numbers is not merely inherent to magnitude, but may be constructed and even changed during task execution, on the basis of the required strategies. For example, in parity judgment task the SNARC effect emerged after memorizing ascending (e.g., 3 4 5) or non arbitrarily-ordered (e.g., 3 5 4) number sequences, but not with descending (e.g., 5 4 3) number sequences (Lindemann et al., 2008). This evidence cannot be explained considering a long-term association between numbers and space (i.e., the *mental number line* hypothesis), but it may be accounted for by assuming a temporary representation linked to the order of the number sequence in memory. Accordingly, task instructions can reverse the SNARC effect in Israeli speakers, depending on the dimension emphasised in task requirements. The singular situation of Hebrew letters gives the opportunity to directly compare ordinal and magnitude processing with the same stimuli, as letters can be read both as numbers and as letters. Crucially, when the task was judging letters as appearing before or after a reference letter in the alphabet, i.e., the ordinal meaning of letters, a right-to-left SNARC effect congruent with the Hebrew reading and writing direction emerged, while when participants had to judge whether the numerical value associated with letters was smaller or larger than a reference number, i.e., the magnitude meaning of letters, a left-to-right SNARC effect arose (Shaki & Gevers, 2011).

Recently, taking into account the influences of context and task demands, the potential role of working memory in inducing spatial mapping has been considered by evaluating the effect of working memory load on spatial effects. First, it has been shown that the SNARC effect disappears when visuo-spatial working memory is loaded (Herrera et al., 2008), indicating that visuo-spatial working memory resources are required in order to observe the SNARC effect in a magnitude comparison task. Additionally, it has been reported that a verbal working memory load abolished the SNARC effect in a parity judgment task (Van Dijck et al., 2009). This evidence suggests that verbal or visuo-spatial working memory are alternatively recruited depending on the task demand and, more critically, that the presence of the SNARC effect is closely dependent on available working memory resources.

Importantly, both the occurrence of spatial compatibility effects for arbitrary overlearned stimuli (van Opstal et al., 2009; Previtali et al., 2010) and the evidence for the working memory role in the emergence of numerical spatial associations (Herrera et al., 2008; Van Dijck et al., 2009) suggest that is the position of numbers in working memory and not their long-term position on a mental number line to be responsible for spatial compatibility effects (Fias et al., 2011). Very recently, these two accounts have been directly contrasted (Van Dijck & Fias, 2011), asking participants to memorize a random series of five numbers and to perform successively a parity judgment task only on the numbers included in the memorized sequence. Results showed that number magnitude had no influence on number-space association, but, critically, the position of numbers in the memorized sequence was associated to space, giving rise to a *positional* SNARC effect, i.e., numbers at the beginning of the sequence were responded to faster with the left hand than with the right hand, while numbers towards the end of the sequence were responded to faster with the right hand than with the left one, independently of their magnitude. Interestingly, this result has been replicated using arbitrarily ordered fruits and vegetables instead of numbers.

Yet, the correlation between the *positional* SNARC effect and the canonical SNARC effect in a parity judgment task was significant, confirming that is the association of the working memory positions with space, not the long-term numerical magnitude, that determines the *magnitude* SNARC effect (*working memory account*, Van Dijck & Fias, 2011). Consequently, in absence of specific instructions or non-canonically ordered stimuli (e.g., descending ordered numbers sequence, e.g., 6 5 4), participants spontaneously use the inherent ordinal structure of numbers, mapping numbers as a function of their numerical magnitude thus, yielding naturally a *magnitude* SNARC effect.

The aim of the present study was to further explore the *working memory account*, investigating the relevance of both magnitude information and working memory task-set, adopting the same procedure of Van Dijck & Fias (2011). Particularly, it has been previously shown that parity judgment and magnitude comparison tasks address to different types of spatial information (verbal and visuospatial, respectively) (Van Dijck et al., 2009) and, while magnitude comparison explicitly accesses magnitude information, in the parity judgment this access is implicit (Priftis et al., 2006). Furthermore, in magnitude comparison the mapping of numbers to responses is intrinsically visuo-spatial, as all numbers that are smaller or larger than the referent one are associated with the same response side, while in parity judgment response side alternates with each number. Thus, if the magnitude information appears inherently related to space, with a newly ordered numerical sequence (e.g., 9 6 4 8 2) we expect to observe a *positional* SNARC effect in a parity judgment (Experiment 7; Van Dijck & Fias, 2011) and a standard *magnitude* SNARC effect in a magnitude comparison task (Experiment 8). Otherwise, if the position of numbers in working memory is the dominant determinant for the spatial associations, the same *positional* SNARC effect should emerge whatever the implied dimension (i.e., parity status or magnitude).

Another factor that should modulate the *working memory account* is the relevance of the memorized sequence. In particular, in the go/no-go paradigm (Experiments 7 and 8) only the numbers belonging to the working memory list have to be judged (Van Dijck & Fias, 2011), making the new ordinal information relevant for response categorization. In order to investigate the relevance of positional information, participants were asked to classify every presented numbers (i.e., from 1 to 10), again maintaining a number sequence in memory, in both parity judgment (Experiment 9) and magnitude comparison (Experiment 10) tasks. If the range of numbers relevant for the response drives the number-space associations, with these two experiments we should observe a typical *magnitude* SNARC effect, as the 1-to-10 range will be presented.

2. Experiment 7

Aim of the first experiment is to replicate previous results concerning the association between position in working memory and space (Van Dijck & Fias, 2011), by requiring subjects to perform a parity judgment task during a verbal working memory task.

2.1 Method

2.1.1 Participants

Twenty-two Belgian subjects (2 males, 1 left-handed), mean age 21 (SD = 2.8) participated in the experiment as volunteers. All participants were naive with respect to the experimental hypotheses.

2.1.2 Procedure

Participants were individually tested in a quiet, dark room. They sat about 50 cm away from the screen. Subjects were instructed to memorize an order sequence of five digits (ranging from 1 to 10; 0.6 by 0.5 cm). Each sequence started with a fixation point (200 ms) and participants chose the presentation time, pressing a button for moving on the following digits. After a 2500 ms period, allowing rehearsal, the parity judgment task started. Arabic numbers from 1 to 10 were randomly presented twice and subjects were instructed to respond only to the numbers that were part of the memorized sequence. A trial consisted of a fixation point (500 ms) followed by a target that disappeared after 1500 ms if there was no response. Subjects pressed one of two response keys as a function of parity status, and the left-/right-hand key assignment was reversed in a second block of trials. This order was counterbalanced across participants. After response, an inter-trial interval of 1000 ms occurred before the next trial was initiated. After the parity judgment task, a series of digits was presented one by one (1000 ms, ISI 200 ms) in the centre of the screen and participants had to indicate whether it was identical or not to the memorized sequence pressing a button (Fig. 4.1). The sequence was correct in half of the blocks and in the other half it differed by two adjacent elements whose position was switched (switches could occur for all elements of the sequence with equal probability). All blocks in which the response was not correct were repeated at the end of the experiment. Twenty different sequences were presented (ten for each key assignment). Each block started with one practice sequence, not further analysed. Memory sequences and no-go trials were constructed such that over the entire experiment, each number appeared an equal amount of times on each position in the memory sequence and as a no-go trial.

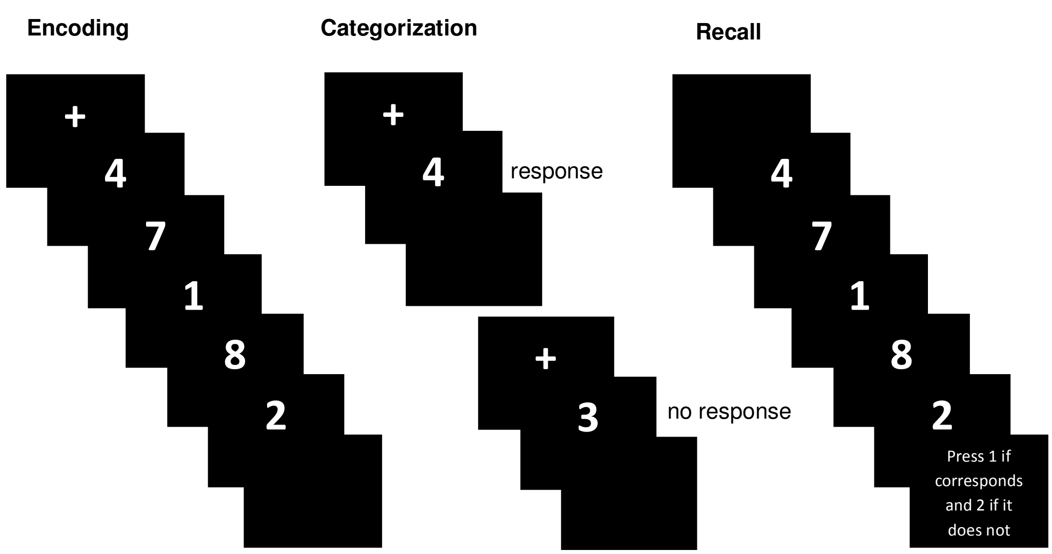

Fig. 4.1. Procedure: encoding, categorization and recall phases.

2.1.3 Results and discussion

Data from two participants were discarded because of too low performances, one took 32 sequences before performing correctly the entire recall task and the average RTs of the other was 2.5 SD above the overall group mean (1067 ms).

It took on average 21.75 (SD = 1.97) blocks before all 20 sequences were correctly recognized. During parity judgment, the average RTs was 796 ms (SD = 237 ms) and the average error rate judging the parity status was 6.42% (SD = 4.19%).

For each participant, median RTs were computed and subjected to a 2 x 5 x 2 repeated measures ANOVA with *magnitude* (small vs. large), sequence *position* (1–5) and *response* (left vs. right) as within subject variables. The ANOVA revealed only a main effect of position [$F(4, 76) = 8.11$, $p < .0001$]. Average RTs per position were 742, 756, 766, 807 and 812 ms. Regression analysis confirmed that RTs increased with 19.4 ms per position [$t(19) = 3.399$, $p < .0001$], suggesting a serial scanning strategy. No other effects or interactions were significant. In order to specifically investigate the serial position effect, a regression analysis for repeated measures data was applied (Lorch & Myers, 1990; see also Fias et al., 1996). One-tailed t test was performed to test whether the regression weights obtained with position in the sequence as predictor deviated significantly from zero. This analysis showed an association of the initial items of the list with left handed responses and the final items with right handed response, as dRTs decreased with 12.71 ms per position [$t(19) = -2.062$, $p < .05$] (Fig. 4.2).

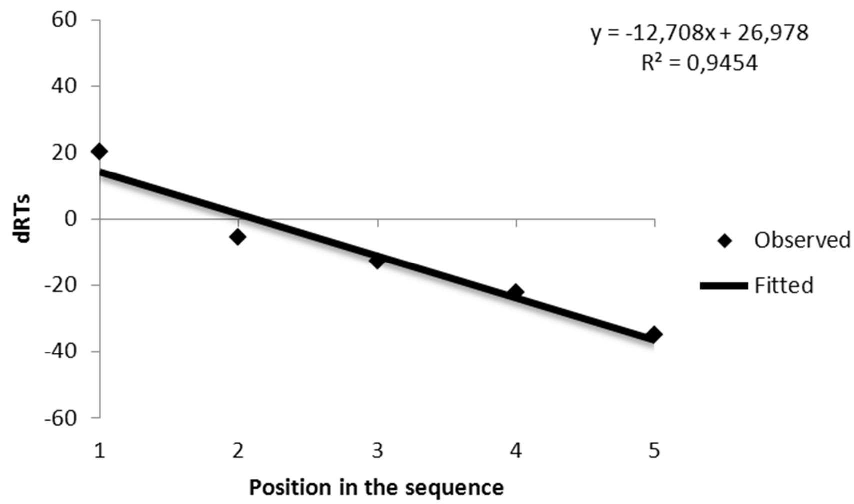

Fig. 4.2. RT differences between right- and left-hand responses in function of position in the working memory sequence.

The same method was adopted with numerical magnitude as predictor and the individual regression weights did not differ from zero [$t(19) = -.034$, $p = .49$] (Fig. 4.3).

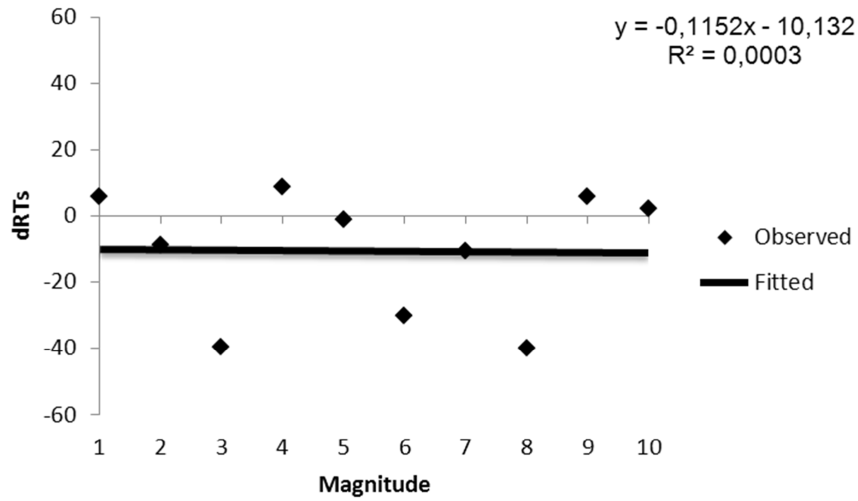

Fig. 4.3. RT differences between right- and left-hand responses in function of numerical magnitude.

The Experiment 7 replicated the results of Van Dijck & Fias study (2011), confirming the *working memory account* for the SNARC effect. Indeed, adopting a newly ordered numbers sequence, initial elements of the sequence were responded to faster with the left hand than with the right hand, while final elements were responded to faster with the right hand than with the left hand. On the contrary, the numerical magnitude has no influence on the spatial association, as the typical *magnitude* SNARC effect did not emerge. This suggests that spatial–numerical associations have their origin in the positional coding in working memory.

3. Experiment 8

In Experiment 8 the role of magnitude information has been directly investigated, exploring whether the magnitude coding is affected or not by the short-term memory association between position and space. Given that the long-term association between magnitude and space is supposed to be more explicit when magnitude is directly accessed, with a magnitude comparison task we expected to observe a *magnitude* SNARC effect. The procedure was the same of the Experiment 7, but participants were asked to perform a magnitude comparison task, responding with the left (or right) hand if the number was smaller than 6 and with the right (or left) hand if the number was larger than 5.

3.1 Participants

Fourteen Belgian subjects (5 males, 1 left-handed), mean age 20 (SD = 2.7) participated in the experiment as volunteers. All participants were naive with respect to the experimental hypotheses.

3.2 Results and discussion

One participant was removed from the analysis because his average RTs was 2.5 SD above the overall group mean (1030 ms).

It took on average 22.31 (SD = 2.50) blocks before all 20 sequences were correctly recognized. During magnitude comparison, average reaction time was 797 ms (SD = 238 ms) and the average error rate judging the magnitude was 6.50% (SD = 2.96%).

For each participant, median RTs were computed and subjected to a 2 x 5 x 2 repeated measures ANOVA with *magnitude* (small vs. large), sequence *position* (1–5) and *response* (left vs. right) as within subject variables. The repeated measures ANOVA revealed a main effect of position [$F(4, 48) = 3.46$, $p < .05$]. Average RTs per position were 764, 756, 774, 787 and 820 ms. Regression analysis confirmed that RTs increased with 14.39 ms per position [$t(12) = 2.86$, $p < .01$], suggesting a serial scanning strategy. The interaction between position and side of response was significant [$F(4, 48) = 2.86$, $p < .05$], revealing a position-space association. No other effects or interactions were significant. Regression analysis confirmed the position-space association, as dRTs decreased with 12.84 ms per position [$t(12) = -2.70$, $p < .01$] (Fig. 4.4).

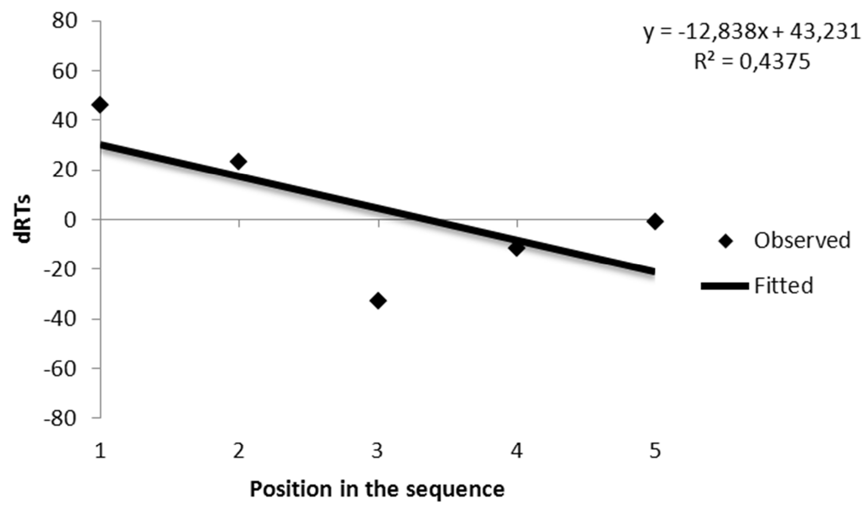

Fig. 4.4. RT differences between right- and left-hand responses in function of position in the working memory sequence.

The individual regression weights of regression analysis with magnitude as predictor did not differ from zero [$t(12) = -0.44$, $p = .34$] (Fig. 4.5).

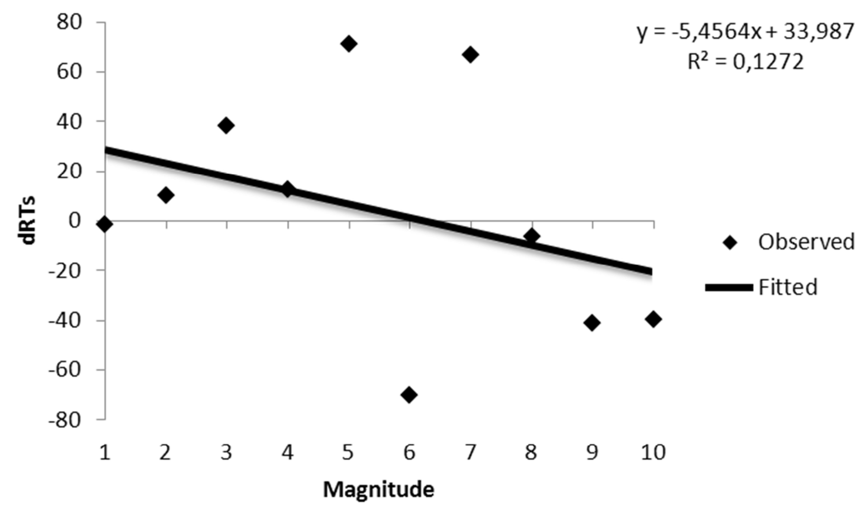

Fig. 4.5. RT differences between right- and left-hand responses in function of numerical magnitude.

Results of the Experiment 8 confirmed, contrarily to the predictions, the existence of an association between position of numbers in the sequence and response side, independently of their magnitude, even if magnitude information was explicitly accessed. The observation of the *positional* SNARC effect and the absence of the *magnitude* SNARC effect, even when magnitude information is relevant to the task, suggest that the dominance of the positional- or magnitude-related coding is influenced by other factors.

In Experiments 7 and 8 working memory set coding was relevant for performing the task (i.e., the go/no-go paradigm), so, potentially, the influence of the ordinal position might originate from the consolidation of position information due to task requirement. The experiments 9 and 10 aimed to explore the influence of the range of numbers in the classification task, removing the go/no-go dimension in the parity judgment (Experiment 9) and in the magnitude comparison (Experiment 10) tasks.

4. Experiment 9

The same task as in Experiment 7 was maintained, removing the go/no-go design, that is, participants were asked to perform the parity judgment on all presented stimuli (i.e., digits from 1 to 10).

4.1 Participants

Thirteen Belgian subjects (6 males, 1 left-handed), mean age 22 (SD = 4) participated in the experiment as volunteers. All participants were naive with respect to the experimental hypotheses.

4.2 Results and discussion

It took on average 22.38 (SD = 2.26) blocks before all 20 sequences were correctly recognized. During parity judgment, average reaction time was 584 ms (SD = 176 ms) and the average error rate judging the parity status was 6% (SD = 4.87%).

For each participant, median RTs were computed and subjected to a 2 x 5 x 2 repeated measures ANOVA with *magnitude* (small vs. large), sequence *position* (1–5) and *response* (left vs. right) as within subject variables. The repeated measure ANOVA revealed an interaction between magnitude and side of response [$F(1, 12) = 10.68$, $p < .01$], indicating the presence of a SNARC effect. No other effects or interactions were significant. The regression analysis confirmed an association between small magnitudes and left-sided response and between large magnitudes and right-sided responses, as dRTs decreased with 7.67 ms per numerical magnitude [$t(12) = -2.92$, $p < .01$] (Fig. 4.6).

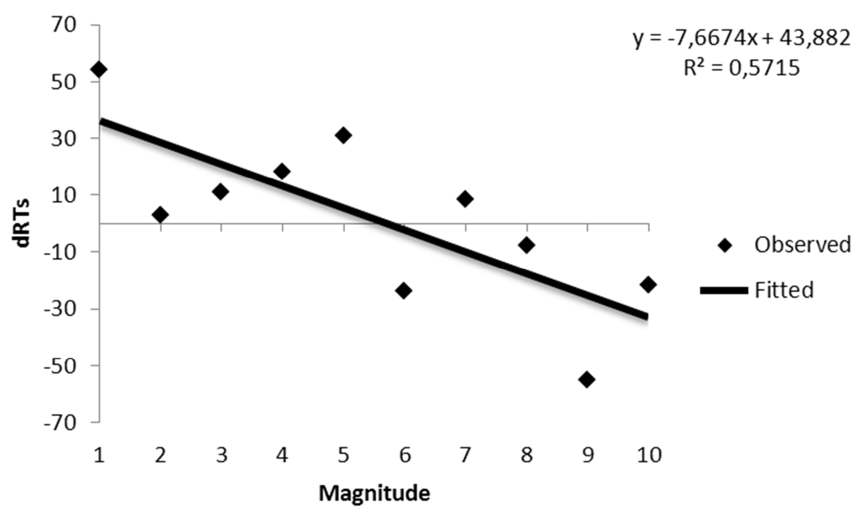

Fig. 4.6. RT differences between right- and left-hand responses in function of numerical magnitude.

The same analysis with position in the list as predictor was not significant [$t(12) = 0.18$, $p = .43$] (Fig. 4.7).

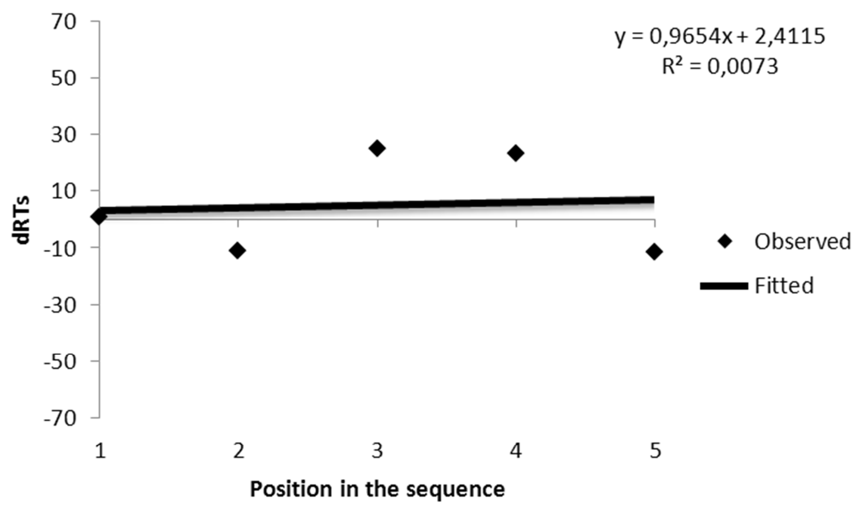

Fig. 4.7. RT differences between right- and left-hand responses in function of position in the working memory sequence.

This pattern of results suggests that in parity judgment the dichotomic categorization of all stimuli might be the crucial factor modulating the SNARC effect. Indeed, in this experiment all presented numbers were categorized, as even or odd, and the *magnitude* SNARC effect was observed, in the absence of a *positional* SNARC effect. Crucially, this pattern of results was reversed compared to the previous go/no-go experiments (Experiments 7 and 8). Thus, it is only the range of numbers used within a single experiment that determines the temporary associations between numbers and space. The last experiment will further investigate the importance of the memory-set relevance, using a magnitude comparison task.

5. Experiment 10

The procedure of this experiment was the same of the Experiment 9, but participants performed a magnitude comparison task instead of a parity judgment task.

5.1 Participants

Sixteen right-handed Belgian subjects (3 males), mean age 21.8 (SD = 3.08) participated in the experiment as volunteers. All participants were naive with respect to the experimental hypotheses.

5.2 Results and discussion

It took on average 20.56 (SD = 0.89) blocks before all 20 sequences were correctly recognized. During magnitude comparison, average reaction time was 541 ms (SD = 168 ms) and the average error rate judging the magnitude was 4.25% (SD = 2.87%).

For each participant, median RTs were computed and subjected to a 2 x 5 x 2 repeated measures ANOVA with *magnitude* (small vs. large), sequence *position* (1–5) and *response* (left vs. right) as within subject variables. The repeated measure ANOVA revealed an interaction between magnitude and side of response [$F(1, 15) = 10.17$, $p < .01$], indicating the presence of a SNARC effect. No other effects or interactions were significant.

The regression analysis confirmed an association between small magnitudes and left and large magnitudes and right, as dRTs decreased with 8.67 ms per numerical magnitude [$t(15) = -3.77$, $p < .001$] (Fig. 4.8).

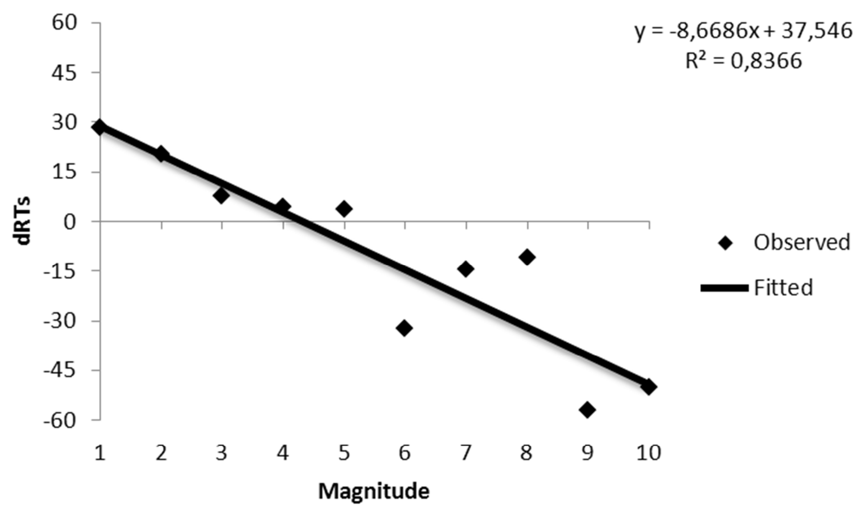

Fig. 4.8. RT differences between right- and left-hand responses in function of numerical magnitude.

The same analysis with position in the list as predictor was significant but indicating a reversed position effect, as dRTs increased with 5.40 ms per numerical magnitude [$t(15) = 2.97$, $p < .01$] (Fig. 4.9).

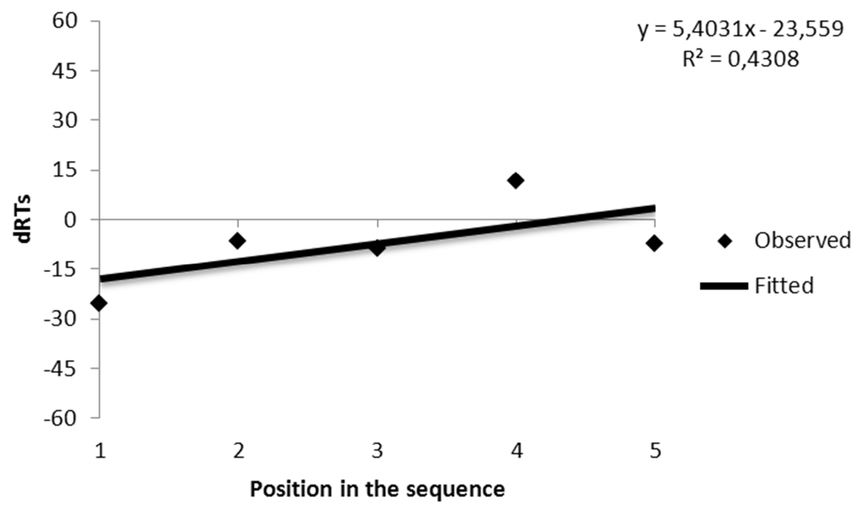

Fig. 4.9. RT differences between right- and left-hand responses in function of position in the working memory sequence.

The results of this experiment confirmed the importance of the link between the range of stimuli-set and response categorization in the *working memory account*. The *positional* SNARC and the *magnitude* SNARC effects seem to have an exclusive relation with each other, as magnitude information (i.e., *magnitude* SNARC effect) is coded in the absence of ordinal (i.e., *positional* SNARC effect) information and vice versa. The presence of a reversed *positional* SNARC effect is still not clear, as no interactions between position and side or between position and magnitude emerged. Hence, this original pattern of results needs to be replicated before asserting any definitive interpretation.

6. General discussion

The aim of this study was to further explore the *working memory account* for spatial-numerical associations (Van Dijck & Fias, 2011), by verifying which factors could explain the occurrence of short- (i.e., the *positional* SNARC effect) or long- (i.e., the *magnitude* SNARC effect) term memory spatial representation of numbers. The first two experiments (7 and 8) have substantially confirmed the spatial mapping of a newly ordered sequence of numbers. The Experiment 7 has replicated a previous result (Van Dijck & Fias, 2011) that is, performing a parity judgment task on numbers belonging to a memorized 5-digits random sequence, a *positional* SNARC effect emerged. This is indicated by faster left than right hand responses for items from the beginning of the memorized sequences and, on the contrary, faster right than left hand responses for items towards the end of sequences. According to this *positional working memory account*, during the execution of number classification tasks, temporary position-space associations between the set of stimuli and responses are created, generating spatial compatibility effects (e.g., SNARC effect). Spontaneously, these associations correspond to the mapping of numbers as a function of numerical magnitude and give rise to the typical *magnitude* SNARC effect, that is, small numbers (e.g., from 1 to 4) are preferentially responded to with the left hand and large numbers (e.g., from 6 to 9) are responded to faster with the right than the left hand. Specific task-contexts can change this default mapping, generating for example the *positional* SNARC effect (Experiments 7 and 8).

Specifically, the *positional* SNARC effect is not influenced by magnitude information, as it has been observed also in the magnitude comparison task (Experiment 8). According to the *mental number line* hypothesis (Dehaene et al., 1993), the numerical magnitude is the dimension that establishes an intrinsic order to numbers (i.e., from number 1 to forward) and the long-term mental representation follows this order. However, the Experiment 8 reveals that even when magnitude is directly processed (i.e., comparing numerical magnitudes) the association between ordered numerical magnitude and space (i.e., the *magnitude* SNARC effect) does not emerge. On the contrary, an association between ordinal position of numbers in working memory and space (i.e., the *positional* SNARC effect) was found, confirming the presence of numbers coding as a function of their, intrinsic or induced, serial position.

Importantly, it is rather the range of stimuli that has to be categorized, and consequently linked to responses, that determines the coding strategy. In fact, in Experiments 7 and 8 only the numbers belonging to the memorized sequences were classified (i.e., a go/no-go task) and the *positional* SNARC effect emerged in both experiments. On the contrary, maintaining the performance of the working memory task (i.e., the memorization of 5-digits-sequences) during numbers categorization, but including also the classification of out-of-sequence numbers (i.e., the no-go trials of Experiments 1 and 2), the pattern of results reversed (Experiments 9 and 10). Indeed, the *magnitude* SNARC effect emerged in the absence of the *positional* SNARC effect, both in parity judgment (Experiment 9) and in magnitude comparison (Experiment 10) tasks. These perfectly asymmetrical results of go/no-go experiments (7 and 8), showing a *positional* and not a *magnitude* SNARC effect, and the experiments without the go/no-go design (9 and 10), showing a *magnitude* and not a *positional* SNARC effect, well reflect the range dependency effect (Dehaene et al., 1993; Fias et al., 1996). When only working memory set was relevant to the response (i.e., the go/no-go design, Experiments 7 and 8) only those specific numbers were coded and strategically mapped determining the association of numbers from the beginning of the sequence with the left hand and numbers towards the end of the sequence with the right hand. On the other side, when the whole 1-to-10 range of numbers has been categorized (Experiments 9 and 10) the corresponding spontaneous mapping of small numbers to the beginning and large numbers to the end of the task-set sequence has been found.

In conclusion, the spatial coding of numbers appears as a cognitive coding strategy in which magnitude- or position-related information are associated to the dichotomic response set, depending on the task context, i.e., instructions, range of numbers, and task execution. This could explain the reverse SNARC effect when numbers are imagined on a clock face (Bachtold et al., 1998) and the modulation of the SNARC induced by the spatial location of numbers on a page during reading (Fischer et al., 2010). Finally, the *working memory account* easily offers an explanation for the flexibility of number-space associations, even if only further investigations will determine whether and how position and magnitude information coexist and especially interact, integrating recent computational models that well account for positional coding (Botvinick & Watanabe, 2007).

Chapter 5

General discussion and conclusions

The results of the present thesis contribute to our understating of the mechanisms underpinning the spatial mental representation of ordinal information. So far, the majority of researches on the spatial organization of ordered sequences focused on the most representative and over-learned ordinal series, that is, numbers (for a recent review see Wood et al., 2008). The influential assumption of a mental representation of numbers conceived as spatially organized from left-to-right (i.e., the mental *number line* hypothesis, Dehaene et al., 1993) promoted an extensive and productive line of research that gradually extended to the investigation of how other non-numerical ordinal sequences are mentally represented. Similarities in both behavioral and neural evidence on the spatial representation of quantities and of non-numerical ordered information support the hypothesis of common mechanisms responsible for processing sequential elements of any sort (Gevers et al., 2003; Rusconi et al., 2006). Despite intensive research in this direction, several crucial questions are still open requiring further and targeted testing. For example, which are the determinants that induce the spatial direction of the mental numerical (and non-numerical) representations? Furthermore, is the spatial organization distinctive of typically ordered information such as quantities, months, letters, or does it apply to any newly and arbitrarily ordered sequence? In addition, if any memorized sequence may evoke spatial associations, how this phenomenon fits with the *mental number line* representation? Can this concept fully account for the reported number-space interactions?

The studies presented here have addressed these questions investigating the origin of numerical and ordinal spatial associations with reference to recent interpretations grounded on memory resources in mediating spatial coding (Van Dijck & Fias, 2011).

1. The role of finger counting direction in mapping numbers onto space

The origin of number-space associations has been recently attributed to the finger counting habits, especially to the direction that individuals prefer when they count on fingers (*"manumerical" cognition* hypothesis; Fischer, 2008). According to this interpretation, the finger counting preference would influence the direction of the SNARC effect, that is to say that individuals starting to count with their left hand should show a left-to-right oriented mental numerical representation (i.e., small numbers counted on the left hand would be easily associated with the left-hand responses and large numbers with the right-hand responses) while, on the contrary, individuals starting to count with the right hand should exhibit a right-to-left numerical mapping, or at least, a weaker spatial mapping (Fischer, 2008).

The study presented in Chapter 2 moves from this assumption, testing to what extent the spatial-numerical associations as indicated by the SNARC effect depend on how people count on their fingers. In particular, once established the consistency in finger-number mapping during counting (Experiment 1b) and montring (Experiment 1c) tasks, participants were presented with a standard parity judgment task (Experiment 2) searching for the SNARC. Results showed a conventional left-to-right SNARC effect in all participants whether they counted on fingers starting with the left hand or with the right hand. Accordingly, this would imply that numerical magnitude (i.e., small or large) was preferentially associated to a lateralised response (i.e., left or right) independently of finger counting direction. Hence, the first key result of this study was to verify that the *embodied* number-space association built up from finger counting routines does not obligatory shape the spatial mapping of numbers at the representational level. In fact, the recent proposal of an origin of spatial-numerical associations linked to finger counting habits (Fischer & Brugger, 2011) cannot explain the same SNARC effect direction (i.e., an index of number-space association) in participants exhibiting an opposite direction in finger counting.

Although the influence of finger counting routines in shaping the spatial mapping of numbers has been convincingly described (Di Luca et al., 2006; Sato et al., 2007; Domahs et al., 2010), controversial evidence indicating asymmetries between finger counting habits and numbers processing are not missing. For example, a very recent study on Italian pre-schoolers revealed no stable relationship between the *embodied*, i.e., related to finger mapping, and *disembodied*, i.e., related to the spatial arrangement of the counted elements, mapping (Rinaldi & Girelli, 2011). Particularly, children counting right-to-left on their fingers (*embodied* mapping) pointed left-to-right while counting elements in the extra-personal space (*disembodied* mapping) and vice versa, indicating a not stable directional correspondence between finger-number mapping and space-number mapping. Furthermore, an analogous SNARC effect was observed in both blind and sighted adults (Castronovo & Seron, 2007; Sallilas et al., 2009) despite the reduced use of fingers in blind children (Crollen et al., 2011). These results suggest caution in indicating a strict connection between spatial numerical mapping and finger counting direction. Although the influence of finger counting mapping (i.e., *embodied*) on number processing is unquestionable, it might well be not the only determinant of the numerical spatial mapping, since several *disembodied* mapping are likely to interact with it. In fact, some evidence points to the primacy of *disembodied* mapping when coexisting space- (i.e., *disembodied,* e.g., related to the mental number line) or body- (i.e., *embodied,* e.g., finger counting) based representation of numbers are in competition (Brozzoli et al., 2008).

In conclusion, converging evidence favours the hypothesis of multiple spatial mapping of numbers, partly determined by the early and extensive used of body effectors to keep trace of the counting sequence and partly induced by general and conventional spatial coding of the perceptual information (e.g., related to visual scanning habits). Is the priority of future research to clarify the way in which these multiple numerical mapping coexist and interact, and eventually, which contextual factors determine the prevalence of one or another of these representations.

1.1 The role of handedness in shaping finger counting direction

Another important goal of the study reported in Chapter 2 was to test the role of handedness in predicting finger counting direction in the Italian population. Finger counting practice has been assessed directly observing the subjects' motor action, investigating both finger counting (Experiment 1b) and montring (Experiment 1c) (i.e., the way people show quantities with their fingers) habits in Italian young adults, focusing on the link between handedness and finger counting direction.

First of all, the observation of counting practice showed that Italian participants displayed a typical finger counting procedure consisting in the consecutive use of both hands with the sequential involvement of all fingers (i.e., from thumb to little finger) (Di Luca et al., 2006; Sato et al., 2007; Sato & Lalain, 2008). Previous cross-cultural studies reported the crucial role of cultural factors (i.e., the writing system direction) in shaping number-digit mapping, for example, Iranian subjects adopt a reverse order (i.e., from little finger to thumb) (Lindemann et al., 2011). In Chapter 2 a canonical use of finger in montring numerosities has been observed as well, as the majority of participants represented numerosities adopting previously reported typical configurations (Di Luca & Pesenti, 2008).

More critically, for the first time, the results of the finger counting habits (Experiment 1b) in addition to a handedness questionnaire (Experiment 1a) showed that the direction of the finger counting procedure is closely related to hand dominance as indexed by manual activities, with left-handers mostly starting with their left hand, and right-handers primarily starting with their right hand. Hints for this relationship were already present in the literature, although previous studies based their observation on a strongly unbalanced sample size of left- and right-handers (Sato & Lalain, 2008; Lindemann et al., 2011). The single contribution so far reported including a large sample of left- and right-handers did not report a correlation between handedness and first hand used for counting (Fischer, 2008). Adopting a similar procedure, based on the use of an online survey, a more pronounced left-starting preference among left-handers was reported (Lindemann et al., 2011). These contrasting results could derive from different methodologies, because the use of written questionnaire (Fischer, 2008) might have induced an overestimation of the left-to-right finger-digit-mapping consistent with the dominant writing system. Indeed, when a different method was used, i.e., a motor performance of the finger counting, similarly to the current study, handedness fully accounts for finger counting direction (Sato & Lalain, 2008).

Unluckily, the proportion of left-handers in the whole population is lower than the right-handers, so only cumulative data from finger counting performance of left-handers can provide more stable conclusions on the role of handedness in finger counting habits.

2. The spatial coding of ordered sequences

A further issue addressed in this thesis (Chapter 3) is to what extent the spatial features of the mental representation of ordinal sequences applies to non numerical elements. In particular, it has been showed that not only numbers evoke spatial compatibility effects such as the SNARC, but also other quantities (e.g., time [Ishihara et al., 2008]) and, crucially, sequences that did not imply any sort of magnitude information such as months or letters (Gevers et al., 2003; 2004). On this ground, aim of Experiments 3, 4, 5 and 6 was to establish whether a newly learned ordered sequence would also convey a spatial coding and induce a spatial mapping in the representational space as conventional over-learned sequences.

After memorizing a sequence of words and corresponding images, target stimuli have been classified in order relevant (Experiments 3 and 4), i.e., deciding whether the presented stimulus appeared before or after the reference stimulus in the sequence, or irrelevant, i.e., deciding whether the presented stimulus contains or not the letter "R" (Experiment 5), tasks. Across three experiments, a stable pattern of results has been observed, that is, stimuli at the beginning of the memorized list were responded to faster with the left than with the right hand, whereas elements at the end of the list were responded to faster with the right than the left-hand, mimicking the standard SNARC effect. This indicates an analogous mental representation for numerical and non numerical quantities (e.g., pitches [Rusconi et al., 2006]), ordinal (e.g., months [Gevers et al., 2003]), and non-intrinsically ordered information (i.e., arbitrarily ordered list of words, Experiments 3, 4 and 5). A further marker for similar processing mechanisms for ordered and arbitrarily ordered sequences was the distance effect, observed in newly learned order sequence across the three experiments. Critically, the significant interaction between the position of the stimulus in the sequence and the response side has been observed also in the order irrelevant task, indicating an automatic access to the mental representation of the sequence.

The key result from Experiments 3, 4, and 5 extends the well known association between over-learned ordinal sequences (e.g., numbers and letters of the alphabet) and spatial codes to newly acquired and arbitrarily ordered sequence of elements. In particular, a stimulus–response compatibility effect and the distance effect suggest that even a newly memorized series is mentally represented along a left-to-right spatial medium, similar to more salient ordinal strings (Dehaene et al., 1993; Gevers et al., 2003; 2004).

In conclusion, all these observations allow us to suggest that a left-to-right (in a Western culture) spatial arrangement of information in long-term memory is the preferential way to organize ordinal information, even if mechanisms responsible for this preferential strategy are not yet established. Although a spatial organization for newly acquired ordered information has been previously described (Van Opstal et al., 2009), an automatic access to this representation that does not convey either magnitude or intrinsic ordinal meaning was never reported before.

3. A working memory contribution to the numerical spatial mapping

Two critical aspects emerge from the conclusions of Experiments 1, 2, 3, 4, and 5 (see above). The first remarkable point is the coexistence of different spatial mappings (i.e., *embodied* or *disembodied*) of numerical information, that implies relative flexibility of any spatial compatibility effect (e.g., SNARC and distance effects) induced by the correspondence between numbers and space. This phenomenon has been previously reported in terms of a modulation of the number-space associations depending on the task context (Bachtold et al., 1998), the range of the stimuli set (Fias et al., 1996), the response assignment (Notebaert et al., 2006), and the instructions (Shaki & Gevers, 2011). These observations indicate that numbers are intrinsically but not steadily related to space.

The second key point emerging form Experiments 3, 4 and 5 is that a spatial representation is evoked by ordered sequences even when the ordinal information is constructed during the task (i.e., the order of the sequence is memorized for performing the task). This built online association between sequential positions and space suggests that the spatial coding is not a prerogative of over-learned ordered series (i.e., numbers, time, pitches, letters, months), but may represent a cognitive strategy for performing any classification task of sequential information.

Taken together, these observations indicate that the long-term representation of numbers, conceptualised as a mental number line, cannot explain the task-dependent modulation of number-space associations, as, accordingly, the only predicted mapping should emerge as a fixed left-to-right representation. Moreover, if every sequence of elements (e.g., numbers, letters, and words) may be spatially represented as suggested by Experiments 3, 4 and 5 reported in Chapter 3, and the spatial mapping represents a specific strategy linked to tasks performance, thus working memory resources are clearly implied. Indeed, the strict link between working memory resources and SNARC effect has been previously suggested by means of a dual-task paradigm (Herrera et al., 2008; Van Dijck et al., 2009); moreover these results have been recently extended showing the association between serial position of numbers in working memory and the left and the right side of spatial representation, with initial items being associated with the left and final items being associated with the right (*working memory account*, Van Dijck & Fias, 2011).

Experiments 7, 8, 9 and 10 reported in Chapter 4 explored the working memory account, directly pitting the short-term memory numerical representation (i.e., the association between serial positions and space predicted by the *working memory account*) against the long-term memory numerical representation (i.e., the association between numerical magnitude and space predicted by the *mental number line* hypothesis). Experiments 7 and 8 in Chapter 4 critically strength the hypothesis of a dominance of a positional coding in working memory adding to some initial evidence in this direction very recently reported (Van Dijck & Fias, 2011). Indeed, after memorizing a randomly ordered 5-digits sequence, participants performed different classification tasks to investigate whether the association between positions of numbers in the sequence or magnitude and space emerged.

The first critical result consists in showing that the position of numbers in working memory is the dominant determinant for the spatial association, as the *positional* SNARC effect emerged, i.e., faster left than right hand responses for initial numbers within a memorized sequence and, on the contrary, faster right than left hand responses for numbers towards the end of the sequence, independently of their magnitude. Importantly, this association emerged not only in parity judgment (Experiment 7), but in a magnitude comparison task (Experiment 8). The magnitude information has been repeatedly indicated as inherently related to space and, accordingly, a standard *magnitude* SNARC effect (faster left- than right-hand responses for small numbers and faster right- than left-hand responses for large numbers) is predicted in a magnitude comparison task. However, results of Experiment 8 revealed that even when magnitude is explicitly processed this association does not emerge, confirming the prevalence of numbers coding as a function of their serial position. These findings explain why numbers are uniquely associated to space, but that spatial coding applies even to other quantitative dimensions (Ishihara et al., 2008), ordinal series (Gevers et al., 2003; 2004) and newly learned sequences (Previtali et al., 2010). In conclusion, the systematic ordering of memorized information rather than magnitude has been suggested as the crucial determinant of the SNARC effect (Fias et al., 2011).

Furthermore, the *working memory account* offers also an explanation for the range dependency effect, that is, the association between a specific number and a lateralized position, i.e., left or right, depends on the range in which the number occurs (Dehaene et al., 1993; Fias et al., 1996). In fact, two different experimental designs were compared in Experiments 7 and 8 vs. Experiments 9 and 10, resulting in opposite outcomes. In Experiments 7 and 8 a go/no-go paradigm was adopted and only the numbers belonging to the memorized 5-digits sequence were responded ignoring the remaining single digit numbers. In Experiments 9 and 10 the whole range of numbers from 1 to 10 were classified, even maintaining the 5-digits sequence in memory. With the go/no-go paradigm the *positional* SNARC effect emerged (see above), while, on the contrary, judging the whole range of numbers, the pattern of results reversed, giving rise to the *magnitude* SNARC effect (Experiments 9 and 10), with faster left than right hand responses for small numbers and faster right than left hand responses for large numbers, independently of their serial position. Overall, these results point to the importance of the range of stimuli to be categorized, and consequently linked to responses, in determining the adopted spatial coding strategy.

In conclusion, the experiments presented in Chapter 4 confirm the hypothesis that in numbers classification tasks, temporary position-space associations between the set of stimuli and responses are built up online (Van Dijck & Fias, 2011), generating spatial compatibility effects (e.g., SNARC effect). Spontaneously, these associations correspond to the mapping of numbers along a magnitude continuum as depicted by the *mental number line* hypothesis and give rise to the typical *magnitude* SNARC effect, while specific task-contexts can change this default mapping generating the *positional* SNARC effect.

4. Future perspectives

In the last decades an increasing number of researches in numerical cognition focused on the relation between numbers and space. Despite the remarkable amount of studies addressing this issue a consensus on the origin of this association is still missing. In this regards, several hypotheses have been proposed, i.e., the cultural modulation of the *mental number line* (Zebian, 2005; Shaki & Fischer, 2008), the *categorical* coding (Gevers et al., 2006), the embodied *manumerical* cognition approach (Fischer & Brugger, 2011), the *working memory account* (Van Dijck & Fias, 2011), but none of them has received universal consensus. The present thesis contributes to this line of research by providing evidence on some debated aspects and open questions for future research. For example, with regards to the contrasting results on the role of finger counting in determining the numerical mapping in the representational space (Fischer, 2008; Previtali & Girelli, submitted), it appears critical to carry out cross-cultural studies with the aim to clarify the role of cultural factors (i.e., the reading-writing system). Moreover, since the present study highlighted the predictive role of handedness in shaping the finger counting direction, future research needs to systematically compare left- and right-handed participants to disentangle the role of both handedness and cultural factors in the spatial mapping of numbers.

Finally, with regards to the role of working memory in determining the spatial numerical associations, the evidence reported in the present thesis clearly shows that the spatial mapping extends to any newly ordered series. Yet, it is still not clear whether and how coding strategies and reading direction interact in shaping the direction of positional coding in working memory. In addition, it would be extremely interesting to clarify the linguistic determinants, i.e., the abstract concepts used to tackle the spatial coding of ordered information (e.g., small and large, left and right or odd and even), since verbal instructions seem to be critical in evoking a specific conceptual coding emphasizing a specific conceptual spatial representation (Gevers et al., 2006).

Overall, all these observations should be considered in order to further explore the complex domain of number-space associations, obtaining a complete understanding of how they develop, occur and interact.

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